6th Colloquium of the CNRS GDR № 3322 on
Q. Information, Foundations & Applications – IQFA
Institut d'Optique Graduate School – IOGS
November 18-20 2015

Book of Abstracts

Contents

1 What is IQFA ?

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

The **GDR IQFA**, GDR № 3322 of the Centre National de la Recherche Scientifique (CNRS[1]), is a Research Network supported by the CNRS Institutes of Physics (INP[2]) and of System Sciences & Engineering (INSIS[3]), with which quantum information community is mostly associated. This GDR gathers more than 50 French laboratories through which more than 80 teams are involved.

The goal of the GDR "Quantum Information, Foundations & Applications" is two-fold: first, to establish a common base of knowledge, and second, to use this platform to emulate new knowledge.

The **main key points of the GDR IQFA** 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.

The **GDR is organized along the 8 identified thematics - ART[4] -** that are currently highly investigated all around the world:

- Coherent Manipulation of Qbits – Cmq;
- Entanglement & Non-classical States – Ens;
- New Qbit Devices – Nqd;
- Quantum Communication – Qcom;
- Quantum Information Foundations – Found;
- Quantum Information Storage – QuIs;
- Quantum Metrology – Qmet;
- Quantum Simulations & Processing – Qsp.

For more details, please visit the GDR IQFA webpage: http://gdriqfa.unice.fr/.

1.2 Scientific Committee of the GDR IQFA

Members: Alexia Auffèves (Institut Néel, UPR 2940, Grenoble),
Antoine Browaeys (LCFIO, UMR 8501, Palaiseau),
Thierry Chanelière (LAC, UPR 3321, Orsay),
Eleni Diamanti (LTCI, UMR 5141, Paris),
Pascal Degiovanni (Lab. Physique de l'ENS Lyon, UMR 5672),
Iordanis Kerenidis (LIAFA, UMR 7089, Paris),
Tristan Meunier (Institut Néel, UPR 2940, Grenoble),
Pérola Milman (Lab. MPQ, UMR 7162, Paris),
Simon Perdrix (LORIA, UMR 7503),
Sébastien Tanzilli (Head, LPMC, UMR 7336, Nice),
Nicolas Treps (Secretary, LKB, UMR 8552, Paris),

Administration manager: Nathalie Koulechoff (LPMC, UMR 7336, Nice).

[1] http://www.cnrs.fr/
[2] http://www.cnrs.fr/inp/
[3] http://www.cnrs.fr/insis/
[4] In French: Axes de Réflexion Thématiques.

2 IQFA's 6^{th} Colloquium – Scientific Information

2.1 Welcome !

IQFA's 6^{th} colloquium is mainly organized by the Laboratoire Charles Fabry de l'Institut d'Optique Graduate School (LCF-IOGS[5]). In addition to the IOGS, the Laboratoire Charles Fabry is associated with the CNRS and the Université Paris Sud.

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

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

In total this year, **IQFA's Scientific Committee (see Sec. 1.2) has received 66 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.

Antoine Browaeys (IQFA's Scientific Committee member, President of the 6^{th} colloquium),
Thierry Chanelière (IQFA's Scientific Committee member),
& **Sébastien Tanzilli** (IQFA's Director),

On behalf of IQFA's Scientific Committee.

[5]https://www.lcf.institutoptique.fr/
[6]http://gdriqfa.unice.fr/spip.php?rubrique2

2.2 Program of the colloquium

Wednesday, November 18, 2015

TIME	EVENT
8:30 am - 9:00 am	Opening the Colloquium - A. Browaeys, T. Chanelière, and S. Tanzilli
9:00 am - 10:30 am	New Qbit Devices - NQD (IOGS Theater) - Pascal Degiovanni
09:00 - 10:00	› Quantum networks for computing and communication with diamond spins - *Ronald Hanson, TU Delft (NL)*
10:00 - 10:30	› The Andreev Qubit - *Hugues Pothier, CEA Saclay (F)*
10:30 am - 11:00 am	Coffee break (IOGS Atrium)
11:00 am - 11:30 am	New Qbit Devices - NQD (IOGS Theater) - Pascal Degiovanni
11:00 - 11:30	› Controlling spin relaxation with a cavity - *Audrey Bienfait, CEA Saclay (F)*
11:30 am - 12:00 pm	Quantum Information Foundations - FOUND (IOGS Theater) - Antoine Browaeys
11:30 - 12:00	› Measurement dependence and limited detection nonlocality - *Djeylan Aktas, Université Nice Sophia Antipolis (F)*
12:00 pm - 1:30 pm	Lunch (Cafeteria Ecole Polytechnique)
1:30 pm - 3:00 pm	Quantum Simulations & Processing - QSP (IOGS Theater) - Antoine Browaeys
13:30 - 14:30	› Quantum computation and learning - *Hans Briegel, University of Innsbruck (AT)*
14:30 - 15:00	› Quantum information protocols in Continuous Variable - *Giulia Ferrini, Université Paris Diderot (F)*
3:00 pm - 3:30 pm	Coffee break (IOGS Atrium)
3:30 pm - 5:00 pm	Quantum Communication - QCOM (IOGS Theater) - Eleni Diamanti
15:30 - 16:30	› Selected topics on quantum and postquantum correlations - *Pawel Horodecki, University of Gdansk (PL)*
16:30 - 17:00	› Detector-device-independent quantum key distribution - *Anthony Martin, University of Geneva (CH)*
5:00 pm - 7:00 pm	Poster Session 1 (IOGS Atrium)

Thursday, November 19, 2015

TIME	EVENT
9:00 am - 10:30 am	Entanglement and non-classical states - ENS (IOGS Theater) - Nicolas Treps
09:00 - 10:00	› About states and modes in quantum optics - *Claude Fabre, UMPC - ENS Paris (F)*
10:00 - 10:30	› Experimental generation of optical squeezed cat states by photon adjunction - *Jean Etesse, IOGS (F) / Uni. Geneva (CH)*
10:30 am - 11:00 am	Coffee break (IOGS Atrium)
11:00 am - 12:00 pm	Entanglement and non-classical states - ENS (IOGS Theater) - Nicolas Treps
11:00 - 11:30	› Few Photon Non-linearities using Rydberg Polaritons - *Rajiv Boddeda, Inst. Optique Graduate School (F)*
11:30 - 12:00	› Integrated AlGaAs Source of Highly Indistinguishable and Energy-Time Entangled Photons - *Claire Autebert, Uni. Paris 7 (F)*
12:00 pm - 1:30 pm	Lunch (Cafeteria Ecole Polytechnique)
1:30 pm - 3:00 pm	Quantum Metrology - QMET (IOGS Theater) - Pérola Millman
13:30 - 14:30	› Quantum metrology: an overview of recent results - *Luiz Davidovich, Uni. Federal do Rio de Janeiro (BR)*
14:30 - 15:00	› Quantum-enhanced detection of atomic spins - *Ricardo Jimenez-Martinez, Institute of Photonic Sciences (ES)*
3:00 pm - 3:30 pm	Coffee break (IOGS Atrium)
3:30 pm - 5:00 pm	Quantum Information Foundations - FOUND (IOGS Theater) - Alexia Auffèves
15:30 - 16:30	› Quantum theory without probabilities - *Renato Renner, ETH - Zurich (CH)*
16:30 - 17:00	› Quantum Protocols within Spekkens' Toy Model - *Leonardo Disilvestro, Telecom ParisTech (F)*
5:00 pm - 7:00 pm	Poster Session 2 (IOGS Atrium)
7:00 pm - 9:30 pm	Colloquium's buffet (IOGS Atrium)

Friday, November 20, 2015

TIME	EVENT
9:00 am - 10:30 am	Coherent Manipulation of Qbits - CMQ (IOGS Theater) - Antoine Browaeys
09:00 - 10:00	› Quantum science and technology with superconducting circuits - *Andreas Wallraff, ETH - Zurich (CH)*
10:00 - 10:30	› Coherent control of an artificial atom with few photon pulses - *Lorenzo De Santis, LPN - CNRS (F)*
10:30 am - 11:00 am	Coffee break (IOGS Atrium)
11:00 am - 12:00 pm	Coherent Manipulation of Qbits - CMQ (IOGS Theater) - Antoine Browaeys
11:00 - 11:30	› Observing quantum state diffusion by heterodyne detection of fluorescence - *Philippe Campagne-Ibarcq, ENS Paris (F)*
11:30 - 12:00	› Mixed-element logic gates for trapped-ion qubits - *Ting Rei Tan, National Institute of Standards and Technology (USA)*
12:00 pm - 1:30 pm	Lunch (Cafeteria Ecole Polytechnique)
1:30 pm - 2:30 pm	Quantum Communication - QCOM (IOGS Theater) - Sébastien Tanzilli
13:30 - 14:00	› Quantum Fingerprinting with Coherent States for Multiple Clients - *Niraj Kumar, Télécom ParisTech (F)*
14:00 - 14:30	› Unidimensional continuous-variable quantum key distribution - *Frédéric Grosshans, Université Paris Sud (F)*
2:30 pm - 3:00 pm	Quantum Simulations & Processing - QSP (IOGS Theater) - Antoine Browaeys
14:30 - 15:00	› Universally Reconfigurable Linear Optics - *Chris Sparrow, University of Bristol (UK)*
3:00 pm - 3:30 pm	Coffee break (IOGS Atrium)
4:00 pm - 4:30 pm	Closing the Colloquium - A. Browaeys, T. Chanelière, and S. Tanzilli

2.3 The Institut d'Optique Graduate School (IOGS), and its scientific environment

The Institut d'Optique Graduate School ("Higher school of optics"), nicknamed "SupOptique" or "IOGS", is the leading French *grande école* in the field of optics and its industrial and scientific applications, and a member of the prestigious ParisTech (Paris Institute of Technology). The École supérieure d'optique was opened in 1920, as part of the IOGS, aiming to train engineers and cadres for the French optics industry. It is consequently the oldest institution of higher education and research in optics in the world, and the most important in terms of annual number of graduates.

The IOGS provides an education of high scientific level, specially for former students from the French *Classes préparatoire aux grandes écoles*. It trains engineers to be, in industry and research, the actors of the development of optics in many areas such as telecommunications, biology, energy, materials, nanotechnologies, aerospace engineering. It trains also researchers and teachers in the fields of optics and physics. Through the IOGS, it participates at the world level to the promotion of knowledge and to the development of new techniques in optics.

From the academic research side, most research groups are part of the Charles Fabry Laboratory, which is associated with the CNRS and the Université Paris-Sud. Patrick Georges is the current director of the laboratory. Here are the different research groups of the laboratory:

- Atom Optics (heads: Laurent Sanchez-Palencia & Christoph Westbrook),
- Quantum Optics (heads: Philippe Grangier, Rosa Tualle-Brouri, & Antoine Browaeys),
- Nanophotonics & Electromagnetism (head: Henri Benisty & Jean-Jacques Greffet),
- Lasers (head: Patrick Georges),
- Biophotonics (head: Michaël Canva),
- Non-Linear Materials & Applications (head: Gilles Pauliat),
- XUV & Surface Optics & Applications (head: Gilles Pauliat),
- Imaging Physics & Systems (head: François Goudail).

Within the context of supporting scientific research & colloquiums, the IOGS supports and welcomes the 6th GDR - IQFA colloquium.

3 IQFA's 6th Colloquium – Practical Information

3.1 Registration

The participants' registration will be made available from Wednesday the 18th of November at 7:30 am, at the Atrium of IOGS's amphitheater where the colloquium takes place.

3.2 Internet Connection

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

3.3 Coffee breaks, lunches & buffet

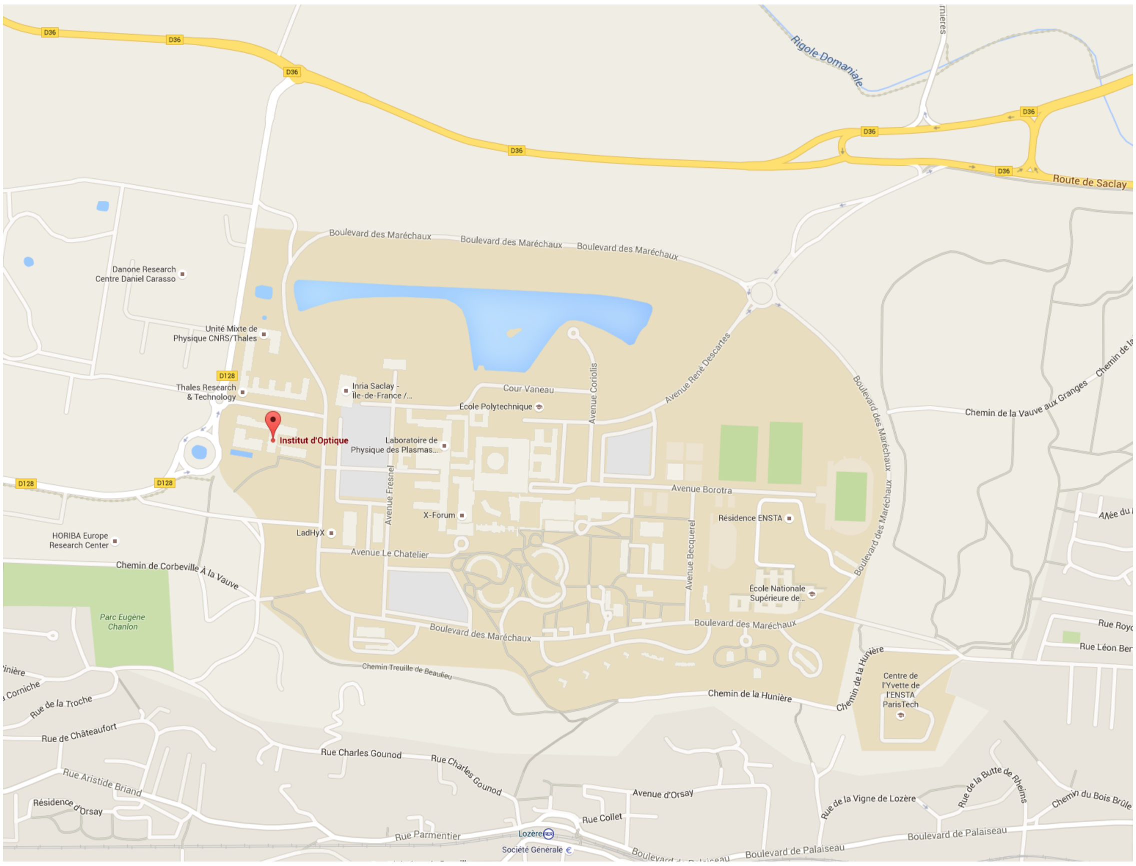
All the coffee breaks during the colloquium will be taken on site, namely in the Atrium. The lunches will be taken at the cafeteria of the École Polytechnique. Coffee breaks and lunches are free of charge for all registered participants.

The dinner of the colloquium will be organized on Thursday the 19th and will be taken on site in the form of a buffet. It will start around 7:30 pm, right after Thursday's poster session (see the program in Sec. 2.2) and is free of charge for people who have mentioned their participation at the early registration stage.

3.4 Venue

IQFA's 6th colloquium will take place at the **Institut d'Optique Graduate School (IOGS) in Palaiseau**. **All the tutorial and contributed talks will be given in the "Amphitheater" inside the IOGS building**. IOGS is accessible using public transportation, as shown by the Localization Maps in Sec. 3.5. Also note that the poster sessions will be organized in the Atrium next to the amphitheater, in the same building.

3.5 Localization map



Localization map of the IOGS and surrounding area.

Access to Institut d'Optique Graduate School in Palaiseau:

- *By public transportation*:
  Go to Massy-Palaiseau, a major public transportation node 15 km South-West of the city center, mainly accessible through the RER B and RER C rapid transit lines, both of which are within easy reach from anywhere in the city of Paris, including all long distance train stations. Direct RER B trains are available from Roissy Charles de Gaulle airport (from Orly airport, use local transit train ORLYVAL to reach RER B at station ANTONY). Note that a few TGV trains call at Masy-Palaiseau TGV, a 2 min walk from Massy-Palaiseau RER B.
  From Massy-Palaiseau, use bus lines 91-06B, 91-06C or 91-10 (bus stop alongside the RER B track, see attached map) to station "Ecole Polytechnique (D128)". The bus stop is in front of Institut d'Optique. Busses run frequently week days 7:00-19:00. (Hickers may use station "Lozère" rather than Massy-Palaiseau and go for a 25 minutes uphill walk).
  Note: special fares apply to all RER rides outside the city of Paris. Purchase a ticket to Massy-Palaiseau. On bus 91-06B, 91-06C and 91-10, use a "t+" urban metro ticket or purchase a ticket from the driver.

- *By road*:
  From A6-A10, exit at "Cité Scientifique" on the left lane to N444, then "Saclay" to D36, take first left

to D128, Institut d'Optique is at the next intersection. From Paris (Western quarters) use N118 from "Pont de Sèvres", follow "Nantes-Bordeaux" to exit 9 "Centre Universitaire", then follow signs to "École Polytechnique". Institut d'Optique is located at the West entrance of École Polytechnique

For more details on how to reach the place of the colloquium, please refer to its webpage at: How to reach the Colloquium[7].

3.6 Organization & financial supports

This colloquium is organized by:	the GDR IQFA,
at, and with the help of:	the Laboratoire Charles Fabry (LCF-IOGS, CNRS, UPSUD),
and with the financial supports of:	the CNRS, through the Institutes INP and INSIS, the Institut d'Optique Graduate School (IOGS), the Université Paris Sud, the Labex PALM, the DIM Nano-K Ile-de-France, ID QUANTIQUE, and MUQUANS,
	that are warmly acknowledged.

3.7 Local organization committee for this colloquium

President:	Antoine Browaeys (LCF-IOGS, UMR 8501, Palaiseau),
Members:	Thierry Chanelière (LAC, UMR 9188, Paris), Thierry Lahaye (LCF-IOGS, UMR 8501, Palaiseau), Nathalie François (LCF-IOGS, UMR 8501, Palaiseau), for admin support,
with the remote help of:	Sébastien Tanzilli, Nathalie Koulechoff, & Bernard Gay-Para (LPMC, UMR 7336, Nice).

[7] http://iqfacolloq2015.sciencesconf.org/resource/acces

4 Abstracts of the contributions

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

Table of contents

Tutorials

About states and modes in quantum optics

Claude Fabre*

Laboratoire Kastler Brossel, Université Pierre & Marie Curie - Paris 6, CNRS, École Normale Supérieure de Paris, France

Quantum Optics, as the child of Optics and Quantum Mechanics, has inherited a double linearity : that of Maxwell equations, which use optical modes as a basis of solutions, and that of the Schrödinger equation, which uses quantum state bases. Considering these two bases on an equal footing and tailoring quantum fields not only in given modes, but also optimizing the spatio-temporal shapes of the modes in which the state is defined, has not been so far fully exploited. This specific feature of Quantum Optics opens wide perspectives for treating complex quantum states. The talk will consider in particular parametrically generated highly multimode quantum states of light, the ways to characterize them and their possible applications to quantum information processing.

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Quantum computation and learning

Hans Briegel*
University of Innsbruck, Austria

We will review recent work on projective simulation (PS), which is a model of artificial intelligence and learning based on stochastic processing of episodic memory. The model of projective simulation can be quantized, providing a quantum speed-up in the decision making of a learning agent. We will discuss applications of learning and the PS model, both in classical environments and in the context of measurement-based quantum computation.

* Hans.Briegel@uibk.ac.at

Quantum metrology : an overview of recent results

Luiz Davidovich*

Instituto de Física, Universidade Federal do Rio de Janeiro, Brazil

Quantum Metrology concerns the estimation of parameters, like a phase shift in an interferometer, the magnitude of a weak force, or the time duration of a dynamical process, taking into account the quantum character of the systems and processes involved. Quantum mechanics brings in some new features to the process of parameter estimation. The precision of the estimation becomes now intimately related to the possibility of discriminating two different quantum states of the probe corresponding to two different values of the parameter to be estimated. Also, possible measurements must abide by the rules of quantum mechanics. At the same time, quantum properties, like squeezing and entanglement, may help to increase the precision. This tutorial talk will review recent results concerning the application of quantum metrology to open systems, with applications to optical interferometry and the quantum speed limit. A quantum-metrology analysis of the problem of weak-value amplification will also be discussed.

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Quantum networks for computing and communication with diamond spins

Ronald Hanson*
QuTech and Kavli Institute of Nanoscience, Delft University of Technology, The Netherlands

The realization of a highly connected network of qubit registers is a central challenge for quantum information processing and long-distance quantum communication. Diamond spins associated with NV centers are promising building blocks for such a network as they combine a coherent optical interface (similar to that of trapped atomic qubits) with a local register of robust and well-controlled nuclear spin qubits. At the same time, the excellent control of NV centers allows for testing and demonstrating fundamental concepts in physics.

In this talk I will explain the scientific concepts and the techniques involved and discuss the most recent results in this field.

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Quantum science and technology with superconducting circuits

Andreas Wallraff*
ETH Zurich, Switzerland

Using modern micro and nano-fabrication techniques combined with superconducting materials we realize quantum electronic circuits in which we create, store, and manipulate individual microwave photons. Making use of the strong interaction engineered between photons and superconducting quantum two-level systems we probe fundamental quantum effects of microwave radiation and develop components for applications in quantum technology. We perform fundamental quantum optics experiments in which we demonstrate the boson nature of single microwave photons in Hong-Ou-Mandel two-photon interference experiments [1], or long range dipole-dipole interaction between qubits [2]. We implement state of the art quantum algorithms or protocols such as deterministic teleportation [3] in electronic circuits, we develop quantum-limited microwave amplifiers [4], we explore measurement technology for and fundamental physics of hybrid quantum systems with both semiconductor quantum dots [5] and Rydberg atoms [6] and we test novel approaches to both digital and analog quantum simulation [7], also in the context of geometric phases [8]. In this presentation, I will give an introduction to the field and discuss a selection of recent results.

[1] C. Lang et al., Nat. Phys. **9**, 345-348 (2013).
[2] A. van Loo et al., Science **342**, 1494-1496 (2013).
[3] L. Steffen et al., Nature **500**, 319 (2013).
[4] C. Eichler et al., Phys. Rev. Lett. **113**, 110502 (2014).
[5] A. Stockklauser et al., Phys. Rev. Lett. **115**, 046802 (2015).
[6] T. Thiele et al., Phys. Rev. A **90**, 013414 (2014).
[7] Y. Salathé et al., Phys. Rev. X **5**, 021027 (2015).
[8] A. Abdumalikov et al., Nature **496**, 482 (2013).

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Quantum theory without probabilities

Renato Renner*
Institute for Theoretical Physics, ETH Zurich, Switzerland

According to the standard formulation of quantum mechanics, the outcomes of measurements have a certain probability distribution, as specified by the Born rule. However, while the Born rule is generally regarded as a postulate of quantum mechanics, the rule does not tell us how these probabilities should be interpreted physically. In my presentation, I will show that the Born rule can be replaced by a weaker postulate which does not involve probabilities. This circumvents the need for an interpretation of the latter. Nevertheless, as I will explain, all experimentally verifiable consequences that are usually derived from the Born rule can still be obtained from this weaker postulate.

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Selected topics on quantum and postquantum correlations

Pawel Horodecki*
Faculty of Applied Physics and Mathematics, Technical University of Gdansk, 80-233 Gdansk, Poland
National Quantum Information Center of Gdansk, 81-824 Sopot, Poland

The original concept of quantum correlations will be presented in terms of entanglement and witnesses. The concept of local hidden variable theory will be discussed together with Bell inequalities and Tsirelson bound. Simple examples will be provided. The links between Bell inequality violation and an effect of reduction of communication complexity will be discussed. Then the concept of no-signaling correlations will be presented and related to quantum correlations. The general monogamy property of the correlations will be discussed. The emergence of quantum correlations as a limit of specific semidefinite programming hierarchy will be discussed. Some of the principles that are supposed to single out physical correlations out of no-signaling ones will be described including, among others, information causality principle. Randomness amplification based on quantum correlations will be finally discussed.

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Coherent Manipulation of Qbits - CMQ

Coherent control of an artificial atom with few photon pulses

L. De Santis[1],* V. Giesz[1], N. Somaschi[1], G. Hornecker[2], T. Grange[2], J. Demory[1], C. Gomez[1], I. Sagnes[1], A. Lemaitre[1], L. Lanco[1,3], A. Auffeves[2], and P. Senellart[1,4]
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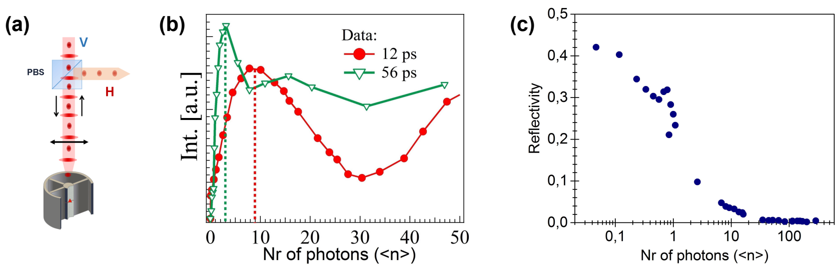
[2]*Université Grenoble Alpes, 38000 Grenoble, France*
[3]*Université Paris Diderot - Paris 7, 75205 Paris, France*
[4]*Physics Department, Ecole Polytechnique, 91128 Palaiseau, France*

The possibility of realizing a quantum network, where the quantum information is coherently transferred between material nodes and photonic channels, has focused a lot of scientific work onto its main challenge : the control of light-matter interaction at the single photon level. Impressive progresses have been recently obtained toward the development of a photonic solid-state quantum network based on quantum dots (QDs), such as the coherent control of QDs [1] and the deterministic coupling of a QD to a cavity [2]. The former led to the generation of highly indistinguishable photons while the latter allowed building an efficient QD-photon interface, with the demonstration of few photon nonlinearities [3] and single photon sources with 80% brightness [4]. Here we report on the first coherent control of a single QD in a cavity. Only few photons impinging on the device are used to generate a π-pulse : the emitted photons present perfect purity and near-unity indistinguishability. In the symmetric situation, where the device is studied to implement photons routing, giant optical nonlinearity is observed at the same few photons scale.

To obtain these results, we have fabricated a micropillar cavity optimally coupled to a single QD using the in-situ lithography technique. The cavity is doped in the p-i-n diode configuration to electrically control the spectral resonance of the QD. A linearly polarized (V) pulsed Ti-Sapphire laser with $10ps$ to $90ps$ pulse is resonant to the mode of the cavity (Fig (a)). The device voltage is adjusted to tune the QD transition in resonance with the laser where a strong increase of the emission is observed. By monitoring the perpendicularly polarized signal (H) as a function of the excitation power, we observe Rabi oscillations in the QD photoluminescence emission (Fig (b)). With pulse duration of $56ps$, the π-pulse is obtained with less than 4 photons sent on the device, evidencing the excellent light matter coupling provided by the micropillar. Monitoring the signal reflected by the device in parallel polarization (V) as a function of the excitation power, we observe the photon-blockade effect on the reflectivity spectrum (Fig (c)). With pulse duration of $70ps$, we obtain a record nonlinearity threshold lower than 2 incident photons per pulse. $g^{(2)}$ measurements shows that the device acts a Fock state filter.



(a) Scheme of the setup.
(b) Resonance fluorescence intensity as a function of the mean photon number of laser pulses
(c) Reflected signal normalized to the maximum reflectivity from the cavity as a function of the mean photon number of laser pulses

[1] Y-M. He et al., Nature Nano., **8**, 213-217 (2012).
[2] A. Dousse et al., Phys. Rev. Lett., **101**, 267404 (2008).
[3] V. Loo et al., Phys. Rev. Lett, **109**, 166806 (2012).
[4] O. Gazzano et al. Nature Communications, **4**, 1425 (2013).

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Coherent controlization using transmon qubits

Nicolai Friis[1], Alexey A. Melnikov[1], Gerhard Kirchmair[2,3], and Hans J. Briegel[1*]
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Extended abstract. Coherent controlization is a process by which an arbitrary (priori unspecified, or "unknown") operation on subsystems is coherently conditioned on the state of a control qubit [1, 2]. This process is important for flexible implementation of many quantum subroutines, e.g. period-finding subroutine in Shor's algorithm and Kitaev's phase estimation subroutine. In addition, coherent controlization plays a pivotal role in the flexible construction of the quantum-enhanced deliberation of learning agents [3] in the context of the projective simulation model for artificial intelligence [4, 5].

The practical realization of coherent controlization requires an auxiliary system in addition to the control and target qubits. However, the details of the implementation depend on the nature of the ancilla system and the type of qubit used. Here, we propose a method [6] that allows coherent controlization in a register of superconducting transmon qubits [7, 8] coupled to an auxiliary microwave resonator. In the simplified case this coupling is described by the Hamiltonian

$$H_{qr}/\hbar = -\sum_i \chi_{q_i r} \boldsymbol{a}^\dagger \boldsymbol{a} \left|1_{q_i}\right\rangle \left\langle 1_{q_i}\right| - \chi_{rr} \boldsymbol{a}^\dagger \boldsymbol{a}^\dagger \boldsymbol{a}\boldsymbol{a},$$

where $\boldsymbol{a}$ is the dressed mode operator of the cavity, $\chi_{q_i r}$ are the qubit-cavity cross-Kerr coefficients and χ_{rr} is the cavity self-Kerr coefficient. Coherent controlization is realized by adjusting the $\chi_{q_i r}$ parameters and by using unconditional cavity displacements with single-qubit rotations conditioned on the vacuum state of the cavity.

We demonstrate that using the described operations it is possible to implement the quantum-enhanced deliberation process of a reinforcement learning agent. The explicit protocols for 2 and 3 qubits are presented and the extension to more qubits via a nesting procedure [9] is discussed. In addition to the ideal protocols we analyze possible sources of errors. In particular, the performance of the protocol under the influence of the cavity self-Kerr effect is analyzed analytically. This effect arises from the strong coupling of the qubits and the resonator. We also show the correction of the imprecise values of the $\chi_{q_i r}$ parameters using an "echo"-type operation as well as the correction of the cross-Kerr between different qubits by appropriate phase gate. And finally, by taking an amplitude and a phase damping of the qubits into account we obtain reasonable fidelities of the 2 and 3 qubits protocols.

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Coherent population trapping of a single nuclear spin under ambient conditions

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Coherent control of quantum systems has far-reaching implications in quantum engineering. In this context, coherent population trapping (CPT) involving dark resonances is a well-established technique which already enable a large range of applications from laser cooling of atoms [1] to metrology [2]. Extending these methods to individual solid-state quantum systems has only been achieved at cryogenic temperature for electron spin impurities [3, 4] and superconducting circuits [5].

In this work, we demonstrate a room temperature CPT of a single nuclear spin in solid. To this end, we make use of a three-level system with a Λ-configuration in the microwave domain, which consists of nuclear spin states addressed through their hyperfine coupling to the electron spin of a single nitrogen-vacancy defect in diamond. Dark state pumping also requires an efficient relaxation mechanism. As no spontaneous decay is present in the system, the relaxation process is externally controlled through incoherent optical pumping and separated in time from consecutive coherent microwave excitations of the nuclear spin Λ-system. Such a pumping scheme with controlled relaxation allows us (i) to monitor the sequential accumulation of population into the dark state and (ii) to reach a new regime of CPT dynamics for which periodic arrays of dark resonances can be observed, owing to multiple constructive interferences [6].

This work offers new prospects for quantum state preparation, information storage in hybrid quantum systems and metrology[7].

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Four nuclear-spin states coherent manipulation

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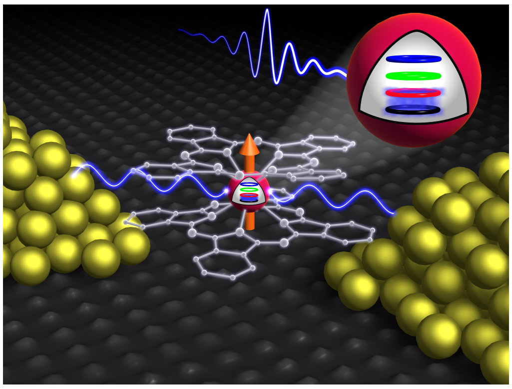
The realization of a functional quantum computer is one of the most ambitious technologically goals of today's scientists. Loss *and al* proposed the use of a 4-level system to implement the Grover's research algorithm [1]. In this context, a single $3/2$ nuclear-spin, embedded in a molecular magnet spin-transistor is of great interest. To solve the algorithm we need to coherently manipulate the four quantum states of this nuclear-spin.

In a recent experiment we validated Di Vincenzo criteria for one nuclear-spin qubit :
- The non-destructive read-out of the nuclear spin state [2] that allows his real-time quantum trajectory measurement [3].
- The coherent manipulation between two nuclear-spin state by means of electric fields [4]
- The storage information by measuring a dephasing time $T_2 = 64\mu s$.

We recently perform Rabi oscillation, Ramsey fringes and Hahn-echo measurements on the three transitions, showing that we are able to coherently manipulate the four nuclearspin states. The next step is to perform an Hadamard gate.



Artist view of a nuclear spin qubit transistor based on a single $TbPc_2$ molecular magnet. The molecule, consisting of a Tb^{3+} ion (pink) sandwiched between two Pc-ligands (white), is coupled to source, drain, and gate (not shown) electrodes. The four anisotropic nuclear spin states of the Tb^{3+} (colored circles) can be tuned and manipulated with electric fields only[4].

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Mixed-Element Logic Gates for Trapped-Ion Qubits [1]

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Precision control over hybrid physical systems at the quantum level is important for the realization of many quantum-based technologies [2]. For trapped-ions, a hybrid system formed of different species introduces extra degrees of freedom that can be exploited to expand and refine the control of the system. We demonstrate an entangling gate between two atomic ions of different elements that can serve as an important building block of quantum information processing (QIP), quantum networking, precision spectroscopy, metrology, and quantum simulation. An entangling geometric phase gate between a $^{9}Be^{+}$ ion and a $^{25}Mg^{+}$ ion is realized through a spin-spin interaction generated by state-dependent forces [3, 4, 5]. A Bell state is created with this mixed-species gate with a fidelity of 0.979(1), and we obtain a sum of correlations of 2.70(2) by performing a CHSH-type [6] Bell inequality test on this state. We also use the mixed-species gate to construct a SWAP gate [7] that interchange the quantum states of the two dissimilar qubits.

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Observing quantum state diffusion by heterodyne detection of fluorescence

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When the relaxation of a qubit comes from its coupling to a photonic channel, each relaxation event is associated with the release of a photon. By counting the photons emitted by fluorescence, discrete quantum jumps of the qubit can be observed. The discreteness of the quantum jumps is in fact related to the nature of the light detector. What does the evolution of the qubit state become if fluorescence is measured using a heterodyne detector instead ? We have used a superconducting parametric amplifier to perform such a continuous measurement of the fluorescence field emitted by a superconducting qubit. Using a stochastic master equation, we reconstruct a different trajectory of the qubit state for each realization of the measured record. Using an independent, and projective measurement of the qubit at various times, we provide a quantitative validation of the reconstructed trajectories. We explore the distribution of states as a function of time and demonstrate that the qubit state spans a surface, and not a volume, in the Bloch sphere representation. Finally, we exhibit trajectories for which the excitation probability counterintuitively increases despite the fact that the corresponding information is encoded in the light emitted during relaxation.

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Entanglement and non-classical states - ENS

A general dichotomization procedure to provide qudits entanglement criteria

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We present a general strategy to derive entanglement criteria through a dichotomization procedure which consists in performing a mapping from qudits to qubits that preserves the separability of the parties and SU(2) rotational invariance. Consequently, it is possible to apply the well known positive partial transpose criterion to reveal the existence of quantum correlations between qudits. We discuss some examples of entangled states that are detected using the proposed strategy. Finally, we demonstrate, using our scheme, how some variance based entanglement witnesses can be generalized from qubits to higher dimensional spin systems.

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Engineering of non-classical states with Rydberg atoms and cavities

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The study of decoherence is a major issue to understand the fundamental limit between the classical and the quantum world.

To explore this transition, it is interesting to study quantum systems where we can easily identify a semi-classical limit, such as an harmonic oscillator, to observe how quantum superposition of macroscopically distinct state evolve under the effect of the decoherence. The mode of an electromagnetic field of the cavity is a perfect example of such system [1]. Through the coupling between the field trapped in a microwave cavity made of two superconducting mirrors and a circular Rydberg atom, we are able to generate non classical state of light as Schrodinger cats [2], and study the effect of the environment on the evolution of our system.

The actual limit of our experimental setup to increase the size of these states remains on the interaction time between the two systems. Presently, the use of a thermal beam at 300 m/s limits us to an interaction time of 30 μs. This is why we are currently building a new setup, where we will prepare Rydberg atoms from a laser cold beam. This allows to reach an interaction time between 10 and 100 times longer than before.

This set up opens the way to new experiments, like the generation of very large Schrodinger cat states as observation of new dynamics of the field [3, 4].

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Entanglement and Semantics : Application to Language Processing

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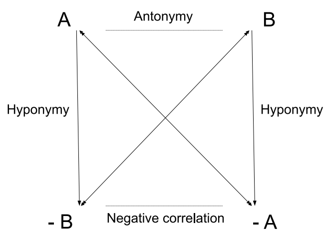
Entangled Bell states have been represented in quantum computation by a $CNOT$ gate whose control Qbit is in an undetermined state. This basic circuit can be useful to represent semantic relationships between two words (lexemes) in a text. Entangled states have been used to detect semantic relationships in Information Retrieval (IR). A lexeme can be represented as a vector in a Hilbert space [1]. Each element of the vector represents the weight of a semantic relation with a second vector : the context of a second lexeme. Two query operators are defined in a way that they attribute the value $+1$ to the component of the state that corresponds to the word meaning we are interested in, and -1 in the orthogonal direction : they correspond to Pauli spin matrices $\widehat{\sigma}_x$ and $\widehat{\sigma}_z$ [4]. In particular, since the first operator corresponds to negation and the conditional gate corresponds to an implication in classical logic, they can represent two basic semantic relationships : hyponymy (e.g. genus-species) and antonymy (e.g. masculine-feminine). In fact, according to Semantics, if *A* and *B* are antonymic terms, then *A* is an hyponym of (i.e. implies) *not-B* [5] as in the semiotic square [6] :



For example, if we consider the New Testament, Matthew, 7, 24-27, "sand" is antonymically opposed to "rock" as it concerns the groundworks of houses. We can represent the relation of entanglement between "rock" and "house" as a $CNOT$ gate between two Qbits. The control Qbit represents the presence/absence of the lexeme "rock". A similar relation of entanglement can represent the relation between "sand" and "house". The antonymy relation can be described by the Z gate. The control Qbits will be in an undetermined state, whose amplitude of probability can represent the strength of the semantic relation, which depends on the distance between the two lexemes in the text according to IR models [4]. We underline how the relations of a given semantic universe, and the corresponding result of our operators, depends only on the considered text : for example, wikipedia defines "sand" as an hyponym of "rock". In terms of structural semantics, entanglement represents the presence/absence of contextual semantic relations (*classemes*). The reason consists in the fact that linguistic categories are relational : for example, a "subject" exists only in opposition to an "object" and does not show any independent, positive identity [3]. Among others [2], this analogy suggests the application of quantum-based models to language and IR.

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Experimental generation of optical squeezed cat states by photon adjunction

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Encoding the quantum information on a propagating system is a major challenge for the quantum information protocols. A possibility to encode this information is to use the continuous degrees of freedom of light through the quadratures, quantum counterparts of the classical phase and amplitude. This way, optical Schrödinger cat states (SCS), superposition of two coherent states $|SCS\rangle = |\alpha\rangle + e^{i\varphi}|-\alpha\rangle$, can be defined as the qubits carrying the information in phase space. Beyond quantum communication, these states find many applications like in quantum computation, quantum error-correcting codes, fundamental testings or precision measurements. But a main challenge related with their use is that they are often required to have a large amplitude, *i.e.* α should be large.

Here, we experimentally demonstrate the validity of the first protocol which allows an iterative growth of SCS, opening the path towards the generation of arbitrarily large amplitude SCS, where the only resources required are single photons and homodyne conditionings. The core protocol consists in mixing two single photon Fock states on a symmetrical beamsplitter, and in realizing a homodyne conditioning in one of the two output ports : if the measurement is close enough to 0, the other port is projected on the state $|\psi\rangle = \sqrt{1/3}|0\rangle + \sqrt{2/3}|2\rangle$, which is close to (99% fidelity) a SCS of amplitude $\alpha = 1.63$ squeezed by $s = 1.52$ along the quadrature x : $|SCS\rangle \simeq 0.61|0\rangle + 0.79|2\rangle + ...$

We have experimentally realized this protocol by using two single photons produced by spontaneous parametric downconversion. For this purpose, two nonlinear type II crystals of $KNbO_3$ pumped with a frequency doubled 2 ps-long pulsed laser at 425 nm were used. With this protocol, we have performed the tomography of the output state, which has 61% fidelity with a perfect SCS of amplitude $\alpha = 1.63$ and squeezing of $s = 1.52$ after correcting 77% efficiency of the homodyne detection [1]. The experimentally created state exhibits a negative Wigner function, even without detection efficiency correction, which is a strong quantum signature.

The strength of this protocol, on the contrary to all the previously proposed ones, is that it can be iterated in order to grow the size of the state : in other word, the state produced here can be put in input of the same protocol in order to produce a bigger cat state. Another impressive fact is that the fidelity of the state increases with an increasing number of stages [2]. Eventually, we also show that this protocol can in fact be generalized in order to produce arbitrary states of light, by using single photon Fock states and homodyne measurements only [3].

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Experimental generation of robust entanglement from classical correlations via local dissipation

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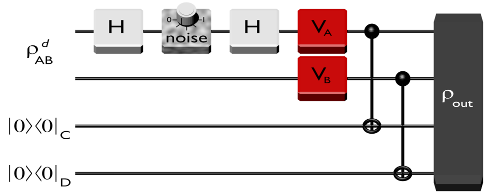
Entanglement has been the acclaimed quantum ressource for many years and separable states were thought to be useless for many tasks in quantum information untill recently. In the last decade, however, another type of non-classicality has been introduced and studied : the quantum discord [1, 2]. This quantity can be non-zero for mixed separable states and expresses the fact that the main difference between classical and non-classical states is that a quantum state cannot be measured without being disturbed. Interestingly, it has been shown [3, 4] that discord can be defined as the minimum amount of entanglement that can be generated through an activation protocol that applies a non-local gate (such as a CNOT gate) between the discordant system and an ancilla. Another interesting feature of discord is that, contrary to entanglement that cannot be generated from local operations, discord can be otained from classical correlations [5, 6] via the use of a particular type of local operations, such as dissipation, which are generally viewed as noise and thus considered to be detrimental to quantum systems.



To illustrate these properties of discord, we propose an experiment (schematized in the figure above) that starts with a classically correlated two-qubit state ρ^d_{AB} and two ancillae C and D. A non-unital noisy device (an amplitude damping channel with an adjustable damping parameter $\eta \in [0; 1]$) sandwiched between two Hadamard gates is applied locally to qubit A, allowing to transform initial classical correlations into discord. Two CNOT gates are then applied respectively between qubits A and C and qubits B and D so as to activate this discord into entanglement in the final four-qubit state ρ_{out}. We allow an adversary player to try and prevent the creation of entanglement by applying any local unitary operations V_A and V_B to qubits A and B before the CNOT gates. We show that the amount of entanglement that can be generated grows with the amount of noise introduced on purpose, we also show that this protocol is robust against the adversary as long as there are non-vanishing classical correlations in the initial state and $\eta \neq 0, 1$.

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Few Photon non-linearities using Rydberg Polaritons

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Quantum states of light are one of the foremost and robust candidates for quantum information transportation and processing. Cold atomic ensembles are a prime choice to store and manipulate the photonic states [1]. Many research groups are currently working on generation and manipulation of quantum states of light using atomic interactions [2–5]. Recently, we have demonstrated efficient retrieval of on-demand single photons from a cavity enhanced cold atomic memory [6, 7].

We are working on realizing "Giant" optical non-linear effects that are able to influence the quantum statistical properties of light at few photon level. These photon-photon interactions would lead to the realization of photonic gates or transistors[8, 9], which are one of the fundamental requirement for quantum computers. It has been shown that an absorptive medium can be made transparent by using destructive quantum interference between two different optical transitions ; this effect is known as electromagnetically induced transparency (EIT) [10]. We are implementing EIT to couple photonic states into atomic memories where the control beam is coupled to highly excited states (n>30) called Rydberg states. Rydberg states are extremely useful in realizing single photon non-linearities because of their strong dipole-dipole interactions over long distances (10μm). We utilize a low finesse cavity to transform phase shifts into intensity correlations that would allow one to generate arbitrary non-classical states of light [11, 12]. We also developed theoretically a protocol for implementing a control phase gate, using a cavity enhanced Rydberg ensemble [13]. We will be presenting our current experimental results on measurement of optical non-linearities using cavity enhanced rydberg ensembles.

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Geometric quantum discords

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The geometric quantum discord is a measure of quantum correlations which has similar properties than the quantum discord proposed by Ollivier and Zurek and Henderson and Vedral [1] to quantify the degree of non-classicality in a bipartite system. It is defined as the minimal distance of the system state to a classical state with respect to one subsystem, that is, to a state with zero quantum discord [2]. The closest classical state(s) to the system state is also of interest and may provide new insight in the problem of the evolution of quantum correlations in time-dependent irreversible processes. We present some new results on the geometric discord and closest classical states when the distance on the set of quantum states is either the Bures or the Hellinger distance. For pure states, the corresponding discords reduce to known entanglement-monotone measures. For mixed states, the Bures geometric discord coincides with the optimal success probability of an ambiguous quantum state discrimination task [3]. This gives an operational interpretation of this discord and establishes an explicit link between quantum correlations and the problem of the distinguishability of quantum states [4]. We show some general relations and bounds between the discords for the Bures, Hellinger, trace, and Hilbert-Schmidt distances and between these discords and similar measures of quantum correlations proposed in the literature, the measurement-induced geometric discord [5] and discord of response [6] . We argue that the Hellinger geometric discord and Hellinger discord of response are simple to compute (we provide explicit expressions when the reference subsystem is a qubit) and are physically reliable, unlike the Hilbert-Schmidt geometric discord proposed initially in Ref. [2].

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Integrated AlGaAs Source of Highly Indistinguishable and Energy-Time Entangled Photons

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Entangled states are key components in quantum information science; in particular, on-chip fully integrated quantum photonic circuits are to play an important role for future quantum technologies. In this domain, the maturity of semiconductor technology offers a huge potential in terms of ultra-compact devices including the generation, manipulation and detection of many quantum bits. Among the different semiconductor platforms AlGaAs present the advantage of a high second order nonlinearity, a mature clean room technology, and a direct band-gap having recently led to the integration of the laser source and the spontaneous parametric down conversion (SPDC) process within the same device [1].

In this paper we report the first demonstration, up to our knowledge, of an AlGaAs source emitting highly indistinguishable and energy-time entangled photons by spontaneous parametric down-conversion. The device is an AlGaAs Bragg reflection waveguide emitting photon pairs at room temperature and telecommunication wavelength; it is based on a modal phase-matching scheme, in which the velocity mismatch is compensated by multimode waveguide dispersion. The structure includes two Bragg mirrors providing both a photonic band gap confinement for a TE Bragg pump mode at 780 nm and total internal reflection claddings for TE and TM modes at 1560 nm.

The source has a brightness of 7.2×10^6 pairs/s with a signal-to-noise ratio of 141. Indistinguishability between the photons is demonstrated through a Hong-Ou-Mandel experiment displaying a visibility of $89 \pm 3\%$. The exploitation of a type II SPDC process makes the device able to produce polarization entanglement [2]. In this work we have chosen to test energy-time correlations, since this is a very convenient format of entanglement, as it can be easily manipulated with integrated circuits and can be preserved over long distances in standard optical fibers [3]. The generated photons are sent through a standard Franson interferometer and the resulting fourth order quantum interference is recorded; the obtained Bell type curve has a net visibility of Vnet $= 95.6 \pm 3.7\%$.

These measurements are a key step for energy-time entanglement and indistinguishable photons generation of electrically driven devices on chip.

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Logical Families of Nonlocal Boxes

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The well known nonlocal PR Box [1] correlates outputs (a, b) to inputs (x, y) in a two-party correlation by means of the logical constarint equation $a \oplus b = x \wedge y$. It violaties the CHSH Bell Inequality (BI) [2] maximmaly : giving the number 4 beyond the quantum limit $2\sqrt{2}$, this last being obtained for a maximally nonlocal entangled quantum state (Bell state). The PR box is also no-signaling.

Here we consider families of boxes with all possible combinations of logical functions f correlated by the equation : $f_o(a, b) = f_i(x, y)$. The indexes o (output) and i (input) correspond to different Boolean functions and the varaibles $(x, y, a, b)\epsilon\{0, 1\}$ are Boolean. There are 16 different Boolean functions for 2 binary variables ($n = 2$), these are ordered with increasing binary number in the truth table : f_0 has the truth table $(0, 0, 0, 0)$, f_1 is NOR $(1, 0, 0, 0)$ and so on... For example OR ($\vee$) is f_{14} $(0, 1, 1, 1)$ and in the PR Box, XOR (exclusive or :$\oplus$) is $f_{o=6}(a, b)$ $(0, 1, 1, 0)$ and AND ($\wedge$) is $f_{i=8}(x, y)$ $(0, 0, 0, 1)$.

We define the joint mean value for the possible outcomes of the box as a function of the marginal probabilities : $C^{(i,o)}_{x,y} = \sum_{a,b}[P(a, b \mid f_o(a, b) = f_i(x, y)) \cdot A \cdot B]$ [3]. The measurement outcomes $A = 2a-1$ (Alice) and $B = 2b-1$ (Bob) give the values ± 1. The Bell parameter considering the four input possibilities is : $S^{(i,o)} = C^{(i,o)}_{00} + C^{(i,o)}_{01} + C^{(i,o)}_{10} - C^{(i,o)}_{11}$. If $S > 2$ we have nonlocality. There are actually four options by changing the place of the "$-$" in the expression of $S^{(i,o)}$. We calculated every case and kept the value of S with the maximal absolute value. We also tested no-signaling by the condition : $P(a \mid x, y) = P(a \mid x)$ and $P(b \mid x, y) = P(b \mid x)$.

For $n = 2$, there are $16 \times 16 = 256$ equations. A family of 16 equations giving maximal violation of the BI ($|S| = 4$) and no-signaling, corresponds to the following combinations of logical functions : output $o : \{6, 9\}$ and input $i : \{1, 2, 4, 8\}$ (8 cases) and also $o : \{6, 9\}$ and $i : \{7, 11, 13, 14\}$ (8 cases). The PR Box is part of this family ($o = 6$, $i = 8$). Another family of 32 equations giving a BI violation $|S| = \frac{10}{3} \approx 3.33 > 2\sqrt{2} > 2$, exceeding the quantum limit, but now signaling, corresponds to : $o : \{7, 11, 13, 14\}$ and $i : \{1, 2, 4, 8\}$, and the converse $o : \{1, 2, 4, 8\}$ and $i : \{7, 11, 13, 14\}$. An example of this kind of nonlocal logical box is : $a \vee b = x \wedge y$ ($o = 14$, $i = 8$).

For three-party correlations, $n = 3$, we have 256 logical functions. The expression of the joint outcome mean value $C^{(i,o)}_{x,y,z}$ is similar as before. We use the Svetlichny BI [4], which is written as follows : $M^{(i,o)} = C^{(i,o)}_{000} + C^{(i,o)}_{001} + C^{(i,o)}_{010} + C^{(i,o)}_{100} - C^{(i,o)}_{011} - C^{(i,o)}_{101} - C^{(i,o)}_{110} - C^{(i,o)}_{111}$, if $M > 4$ we have non-locality.

$n = 3$ corresponds to $256 \times 256 = 65536$ equations. Non-locality is obtained for six different values: $M_{NL} = 8\,; 6.4\,; 6\,; 5.33\,; 4.8\,; 4.57$ with the corresponding number of cases $N_{case}(M_{NL}) = 71\,; 560\,; 112\,; 840\,; 896\,; 560$. The cases of non-locality and non-signaling are less and occur only for $M_{NL+NS} = 8\,; 6\,; 5.33$.

In this work we show that in the case of two-party correlations, we have two families of nonlocal boxes : one with 16 boxes, comprising the PR box, and the other one, to our knowledge unknown up to now, giving 32 nonlocal boxes beyond the quantum limit but signaling. For three-party correlations the number increases and the picture is much more complex.

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Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

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For more than 80 years, the counterintuitive predictions of quantum theory have stimulated debate about the nature of reality [1]. In his seminal work [2], John Bell proved that no theory of nature that obeys locality and realism can reproduce all the predictions of quantum theory. In any local realist theory the correlations between distant measurements satisfy an inequality that can be violated according to quantum theory if the measurements are performed on entangled particles. In the past decades, numerous ingenious Bell inequality tests have been reported [3]. However, because of experimental limitations, all experiments to date required additional assumptions to obtain a contradiction with local realism, resulting in loopholes [3].

Here we will present a Bell experiment that is free of any such additional assumption and thus directly tests the principles underlying Bell's inequality [4]. We employ an event-ready scheme that enables the generation of robust entanglement between distant electron spins (estimated state fidelity of 0.92 ± 0.03). Efficient spin readout avoids the fair sampling assumption (detection loophole), while the use of fast random basis selection and spin readout combined with a spatial separation of 1.3 km ensure the required locality conditions. We perform 245 trials testing the CHSH-Bell inequality $S \leq 2$ and find $S = 2.42 \pm 0.20$. A null hypothesis test yields a probability of at most p = 0.039 that a local-realist model for space-like separated sites could produce data with a violation at least as large as we observe, even when allowing for memory in the devices ; a large class of local realist theories is thus rejected. This result paves the way for further bounding of the statistical uncertainty, for testing less conventional theories, and for implementing device-independent quantum-secure communication[5] and randomness certification [6].

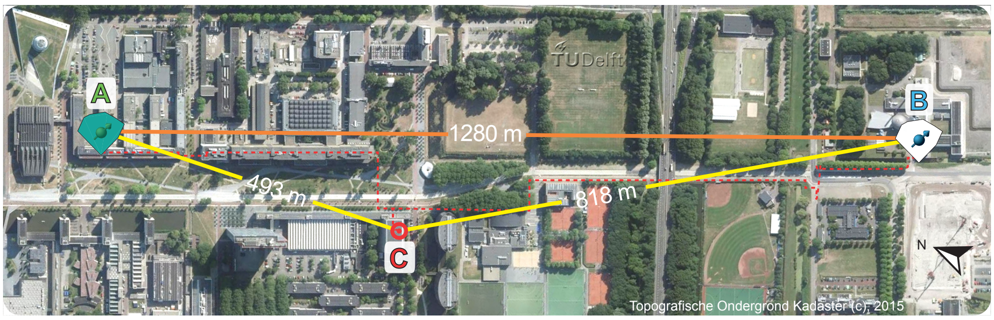

FIGURE 1. Aerial photograph of the campus of Delft University of Technology where entanglement was generated between two electron spins in diamond located at positions A and B. The location C serves as an intermediate station necessary for the remote entanglement protocol. The red dotted line marks the path of the optical fiber connecting the three setups.

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On-chip heralded photon-number states generation

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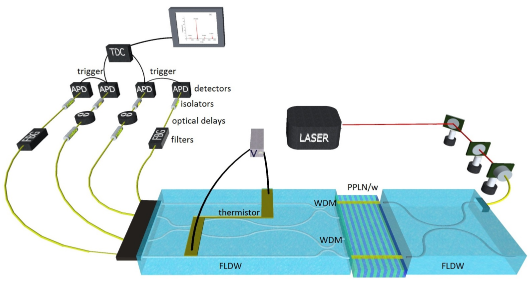
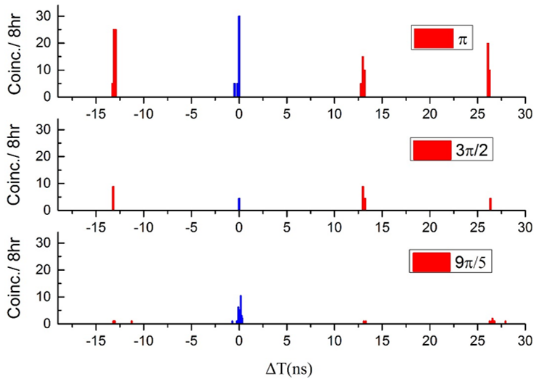
Recent progress in the field of quantum information processing has highlighted the prospects of using integrated optical devices for quantum applications. Integrated quantum photonics offers several advantages compared to free-space setups. Not only the miniaturization, which dramatically reduces the size of the building blocks and allows imprinting or cascading several functions on a single substrate, but also the possibility to reproduce the same photonic circuit many times on the same chip. For instance, this has been exploited to spatially multiplex heralded single-photon, leading to an increase of the single-photon emission rate at constant noise level [1]. More strikingly, one can think of combining, on-chip, several synchronised single photon sources towards engineering large photon-number entangled states.



(a) Photonic Chip.



(b) 4-fold coincidences

FIGURE 1: (a) Set-up and (b) Results.

Despite this attractive potential, only few examples of spatial multiplexing have been reported in the literature due to the technological challenge related to fabrication processes. On one hand, lithium niobate (LN) is very suitable for quantum integrated photonics since it shows both optic-optic and electro-optic non-linearities, as well as the possibility to integrate low-loss waveguides. However, several parallel and/or cascaded optical functions require various lithographic steps leading to reduced yields. On the other hand, femto-second laser direct-writing (FLDW) technique on glass-type substrates, allows fast fabrication of low-loss waveguide circuits requiring no lithographic masks nor chemical exchange. However, no efficient non-linear processes are available in SiO_2 waveguides for photon-pair generation. We discuss here an integrated photonic chip able to generate photon-number states which consists of three photonic chips fabricated on either LN for photon generation or on SiO_2 substrates for photon manipulation purposes (Figure 1a). Our approach takes advantage of the best features of both worlds.

The input chip routes the pump laser pulses in two spatial modes associated to two identical periodically poled lithium niobate (PPLN) sources allowing the generation of pairs of photons spectrally distinguishable (at 1560 nm and 1310 nm) via the process of spontaneous parametric down-conversion. Integrated optical functions ensure the splitting of the photons of each pair and, thanks to an integrated, thermally-tunable, Mach-Zehnder interferometer, the manipulation of heralded photon-number states is achieved. The detection of the two 1310 nm photons in the outer modes, heralds the arrival of the two photons at 1560 nm in the inner modes, encoded in the following quantum state :

$$|\psi\rangle \sim (1 - e^{i2\phi(V)}) \frac{(|20\rangle + |02\rangle}{\sqrt{2}} + 2i(1 + e^{i2\phi(V)}) |11\rangle \,, \quad (1)$$

where the phase $\phi(V)$ can be changed by adjusting the voltage and tune the phase on the interferometer by inserting a temperature gradient between the two arms. Therefore, the source can prepare on demand, either a two-photon N00N or a product state. In Figure 1b it is shown the absence of 4-fold coincidences on the peak of interest (blue) for a phase $\phi(V) = 3\pi/2$, confirming the generation of the N00N state.

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Practical Measurement Device Independent Entanglement Witness

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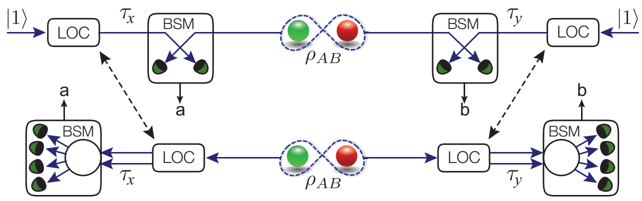
Entanglement is one of the quintessential characteristics of quantum physics and is a valuable resource in emerging quantum technologies. A reliable verification and characterization of entanglement is therefore critical for many applications and protocols. Various methods have been proposed to demonstrate entanglement. One of them uses a so called entanglement witness to distinguish entangled states from separable ones. An entanglement witness is defined such that for a given quantum state ρ and an hermitian operator W, the state is said to be entangled if Tr$[\rho W] < 0$, otherwise it is separable. This standard entanglement witness relies on a perfect implementation of the measurements. Importantly, if there are errors in the implementation of the measurements, then one cannot faithfully witness entanglement. Approaches based on Bell inequalities have been proposed to overcome this problem of device dependency. The violation of Bell inequalities, which guarantees the presence of entanglement, is completely independent of the measurements or the internal workings of the measuring devices. However, these methods require the detection loophole to be closed to ensure that fair sampling has been restricted and one has reliably witnessed entanglement.

A novel solution to this was recently proposed by Branciard *et al.* [1], whereby instead of using classical inputs to perform a Bell test, quantum states inputs are sent to the participating parties -an approach arising out of work on nonlocal games by Buscemi [2]. In this scenario, an entanglement witness which is robust to measurements imperfection can be derived. This measurement-device-independent entanglement witness (MDIEW) provides a new entanglement detection scheme which is tolerant to losses and does not require to trust the detecting devices. Here we introduce a variation of the MDIEW protocol that exploits another recent idea of detector device independent QKD [3]. Instead of preparing ancilla qubits to probe the entangled state [4], a qubit state is encoded in an extra degree of freedom, via a simple linear circuit. In doing this we greatly simplify the experimental overhead to perform MDIEW. With this practical implementation, we characterized the entanglement in SPDC sources, using untrusted detectors and facing high losses. In MDIEW protocols, the requirement to trust measurements is replaced by the requirement to trust the inputs generation. In principle, the input qubit must be prepared exactly as specified in the assumptions. Experimentally, it is often impossible to achieve perfect qubit preparation. Here, we also investigate the impact on the entanglement characterization of systematic and fluctuating errors in the input qubit preparation.



Comparison between previous implementations of MDIEW, in which the inputs are prepared ancilla qubits (upper), and our practical implementation of MDIEW (lower). Our implementation is a two-photons experiment : the input qubit states are encoded in a different degree of freedom via simple linear circuits.

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Quantum Backaction Free Spin-Mechanical System and its Classical Implementation

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Uncertainty principles limit the maximum knowledge attainable about a pair of canonically conjugate variables, bounding from below the precision in a quantum measurement. However, in backaction evading schemes [1, 2], measurements can be taylored in such a way that the backaction noise is decoupled from the observables of interest, leading to quantum noise free experiments. Recently, a proposal [3] of this nature, employing two interacting harmonic oscillators having equal but opposite masses, was shown to lead to backaction free measurements when creating a continuous variable Einstein-Podolsky-Rosen state between the oscillators. Following this proposal, we explore the possibility of backaction evasion measurements in an optically probed, hybrid system consisting of nanomechanical oscillator and an atomic spin ensemble. The nanomechanical oscillator is a Silicon Nitride (Si_3N_4) membrane, placed inside a high-Finesse optical cavity and exhibiting high-Q. The atomic ensemble is Cs vapor at room temperature, contained in a glass cell and precessing around a static magnetic field; Optical Pumping prepares the Cs vapor to an effective negative mass oscillator. As a proof-of-principle for the cancellation of the probe-induced backaction, we experimentally show the reduction in response of the combined hybrid system due to a coherent optical drive. This is an important step towards entanglement in this hybrid system, paving the road to applications in ultra-sensitive measurements of force and magnetic fields.

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Quantum zeno dynamics of the field in a linear microwave cavity with a transmon qubit

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Quantum Zeno dynamics [1] has been proposed to manipulate at will the wave function of the field in an electromagnetic cavity [2]. To observe this dynamics we use a superconducting microwave cavity and a transmon qubit [3]. The cavity has a linear mode with a high quality factor for storing the quantum field, and another low Q mode for measuring the qubit. Strongly driving the qubit at a well defined frequency "removes" a particular Fock state from the high Q harmonic ladder and yields Zeno blockade. We observe the resulting non classical quantum states in various situations.

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Squeezed states of radiation in the THz and mid-IR ranges within the markovian limit

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We propose a method to prepare non-classical states of light in the TeraHertz and mid-Infrared frenquency ranges, in which we use a collective excitation of a cavity-embedded two-dimensional electron gas [1]. By using the coupling of the electron gas with a cavity mode, it is possible to produce squeezed states, due to the existence of the so-called ultrastrong coupling regime [2]. The bosonic description of the quantum well excitations [3, 4], combined with the counter-rotating terms of the light-matter coupling allows the system to emit squeezed light up to -13 dB for a coupling constant equal to one half of the cavity frequency. These results open the perspective in using this solid state systems as tools for quantum optics in the THz and mid-IR ranges.

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New Qbit Devices - NQD

Controlling spin relaxation with a cavity

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Spontaneous emission of radiation is one of the fundamental mechanisms by which an excited quantum system returns to equilibrium. For spins, however, spontaneous emission is generally negligible compared to other non-radiative relaxation processes because of the weak coupling between the magnetic dipole and the electromagnetic field. In 1946, Purcell realised [1] that the spontaneous emission rate can be strongly enhanced by placing the quantum system in a resonant cavity — an effect which has since been used extensively to control the lifetime of atoms and semiconducting heterostructures coupled to microwave[2] or optical cavities[3]. Here we report the first application of these ideas to spins in solids. By coupling donor spins in silicon to a superconducting microwave cavity of high quality factor and small mode volume[4], we reach for the first time the regime where spontaneous emission constitutes the dominant spin relaxation mechanism. The relaxation rate is increased by three orders of magnitude when the spins are tuned to the cavity resonance, showing that energy relaxation can be engineered and controlled on-demand [5]. Our results provide a novel and general way to initialise spin systems into their ground state, with applications in magnetic resonance and quantum information processing.

They also demonstrate that, contrary to popular belief, the coupling between the magnetic dipole of a spin and the electromagnetic field can be enhanced up to the point where quantum fluctuations have a dramatic effect on the spin dynamics ; as such our work represents an important step towards the coherent magnetic coupling of individual spins to microwave photons.

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Hong-Ou-Mandel interferometry as a tool to probe decoherence

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In the past few years, the application of quantum optics concepts in condensed matter systems has opened an emerging field, called electron quantum optics, focused on the measurement, control and manipulation of electronic coherence. This breakthrough was made possible by the recent realization of an on-demand single electron source [1], which has in turn lead to the demonstration of several seminal quantum optics experiments such as the Hanbury Brown and Twiss [2] or the Hong-Ou-Mandel [3] ones at the single electron level.

However, these experiments are more than just analogs of their photonic counterparts. Due to the fondamental difference in statistics between fermions and bosons, several new features appear. Indeed, fermionic statistics lead to the existence of the Fermi sea, a ground state totally different from the vacuum of photon optics. Moreover, electron being electrically charged implies that they will experience Coulomb interactions and therefore strong decoherence effects.

Here, we adress the issue of probing quantitatively decoherence at the level of a single electron excitation (Landau quasi-particle) through Hong Ou Mandel interferometry. Our work [4] confirms the recently elaborated decoherence scenario [5] describing the fate of a single quasi-particle propagating in a ballistic conductor in the presence of strong Coulomb interactions. Our work also shows that Hong-Ou-Mandel interferometry is an efficient tool for probing decoherence effects in a strongly interacting system at the single quasi-particle level.

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Optimal randomness generation from optical Bell experiments

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Quantum systems have the potential to provide a strong form of randomness which cannot be attributed to incomplete knowledge of any classical variable of the system. At the basis of such genuine randomness lies a quantitative relation between the amount by which a Bell inequality is violated [1] and the degree of predictability of the results of the test [2]. Intuitively, the violation of a Bell inequality certifies the presence of nonlocal correlations, and in turn, this guarantees that the outcomes of the measurements cannot be predetermined in advance. Furthermore, this genuine randomness can be certified without any detailed assumptions about the internal working of the devices used, that is, in a device-independent fashion [3].

A few years ago, Pironio et al. [2] implemented the first device-independent random number generation (DIRNG) proof-of-principle experiment. It involved light-matter interaction and managed to certify 42 genuinely random bits over a period of one month. More recently, DIRNG has been observed in entirely optical setups [4], based on polarisation measurements of entangled photons distributed from a spontaneous parametric down-conversion (SPDC) source. These optical setups represent an important achievement as they enable higher rates of random bits per time unit.

Here we construct a general three-step method for optimal randomness generation in bipartite Bell experiments and apply it to such all-optical setups. The first step consists on keeping the whole statistics, which is something that, unfortunately, existing Bell experiments have not considered, as they systematically "bin" the number of outcomes to have only 2 outcomes per party and make use of the well-known CHSH inequality. But actually, optical Bell experiments with bucket detectors (non photon number resolving) provide up to 4 outcomes per site, which, as we show, turns out to be advantageous for DIRNG. The second step is to find the best Bell inequality for randomness considering the whole statistics. Such an optimal Bell inequality can be found with Semi-Definite Programming techniques, following the methods recently introduced in [5]. The final step is to optimize the amount of randomness (certified by the Bell inequality derived in the previous step) over the physical parameters tunnable in the experiment. In optical Bell experiments, such physical parameters correspond to : *(i)* the degree of entanglement ("squeezing") of the SPDC source, *(ii)* the number of modes used to distribute entanglement among the two parties, and *(iii)* the polarization measurement directions of the Bloch sphere.

Our results show that more randomness is certified when : *(i)* the degree of entanglement is maximal, *(ii)* the number of modes and *(iii)* the number of measurements used are as high as possible. We provide other relevant yet unexpected numerical values for the physical parameters and achieve up to four times more randomness than what a standard analysis (based on a binning of the outcomes and on the CHSH inequality only) can achieve. Finally, our results for randomness can be extended to Device-Independent Quantum Key Distribution, and thus are very encouraging for near-future Device-Independent Quantum Information Processing implementations with optical systems.

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Solid State Bright Sources of Fully Indistinguishable Photons

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Bright sources of single and indistinguishable photons are crucial for the scalability of linear optical quantum computing. Recent works have shown that semiconductor quantum dots (QDs) are very promising to fabricate such sources : QD deterministically emit true single photon states which can be efficiently collected if the QD is inserted in an optical structure. Recently, we demonstrated QD-based single photon sources with a brightness of 80% and indistinguishability as high as 92% [1].

Here we report on the fabrication and study of electrically tunable bright sources of fully indistinguishable single photons. We propose a novel cavity design which permits to apply an electric field while maintaining a 3D confinement for the photons. Specifically it consists of a micropillar cavity (2-3 μm) connected to a larger ohmic-contact surface with four 1D-bridges and a surrounding frame. Laterally, the fundamental cavity mode (CM) of the structure is confined in the centre of the connected pillar. Vertically, the GaAs cavity is surrounded by GaAs/AlGaAs Bragg mirrors, doped in a p-i-n diode configuration. A single QD is deterministically positioned at the center of the pillar by means of an advanced in-situ optical lithography [2, 3]. A strong Purcell effect is obtained with such a device when the QD transition is tuned into resonance with the CM, which in turn results in a very high brightness of the single-photon source, exceeding 55%. We study the device at first by mean of non-resonant excitation and report a photon indistinguishability in the $70-80\%$ range. Subsequently we demonstrate that performing strictly resonant pumping in a excitation/detection cross polarization scheme (Fig.1 a) we can suppress completely any dephasing process thus obtaining near-unitary indistinguishability $M = 0.998 \pm 0.0086$ of the emitted single photons ($g^{(2)}(0) = 0 \pm 0.0034$) (Fig.1 b, c).

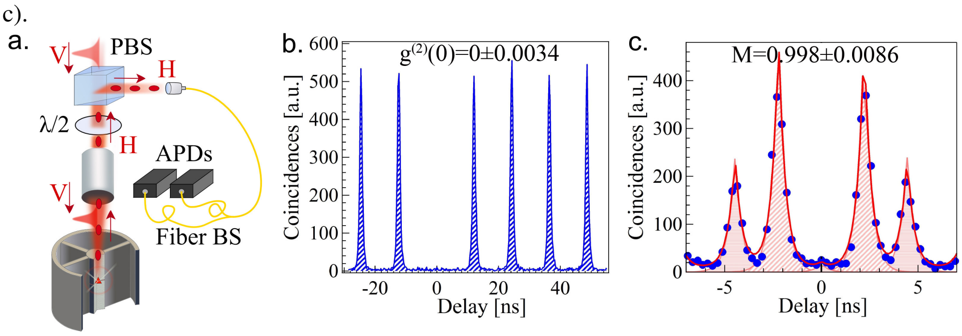

FIGURE 1: a) Schematic of the resonant excitation scheme implemented, based on cross polarization between the exciting pulses and collected photons. b, c) Second order autocorrelation function in a HBT (b) and HOM (c) experiment. The vanishing counts at zero delay in both histograms show respectively perfect single photon purity ($g^{(2)}(0) = 0 \pm 0.0034$) and full indistinguishability ($M = 0.998 \pm 0.0086$) of the source.

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The Andreev Qubit

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Existing superconducting qubits are based on collective electromagnetic modes involving a charge, a superconducting phase or a flux degree of freedom. A non-linearity in the modes introduced by the presence of a Josephson junction allows defining a qubit with the two lowest energy states. In contrast, Andreev bound states occurring in superconducting weak links form true two-level systems. Using the simplest weak link possible, an atomic contact, we have demonstrated the coherent manipulation of Andreev states [1]. I will explain the physics of Andreev states, describe almost-QND measurements of an "Andreev Qbit" in a circuit-QED set-up, and discuss the relaxation and coherence times.

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Quantum Communication - QCOM

Cavity Enhanced Two-Photon Interference with Remote Quantum Dot Sources

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Indistinguishable single-photons are fundamental building-blocks for conceiving long distance optical networks for quantum information. For example, the control of quantum interferences to implement efficient interactions between photons is a key-step for teleportation of quantum states.

Quantum dots (QDs) embedded in microcavity-pillars are promising candidates to realize solid-state bright-sources of single-photons for quantum applications. A few years ago, quantum interferences between photons emitted by two distinct QDs were demonstrated [1, 2]. More recently, ultrabright sources of indistinguishable single-photons were developed by deterministically coupling a single QD to a microcavity-pillar [3, 4].

The next crucial step, addressed in this work, is to demonstrate quantum interferences between two of these bright single-photon sources [5]. In our experiments, one QD-source operates in a regime of strong Purcell effect and emits highly indistinguishable photons, while photons emitted by the second QD-source are mostly distinguishable. When the single-photons emitted from each source are sent to the two inputs of a beam-splitter, a $(40 \pm 3)\%$ probability of two-photon coalescence is obtained (see Fig. 1). The Purcell effect on the first source is shown to partially erase the effect of pure dephasing on the second one. Moreover, the radiatively-enhanced homogeneous broadening of the first source allows obtaining a two-photon interference on a wide spectral range. All observations are fully described theoretically and they demonstrate that cavity quantum electrodynamics is a powerful tool to control on demand the two-sources interference phenomena.

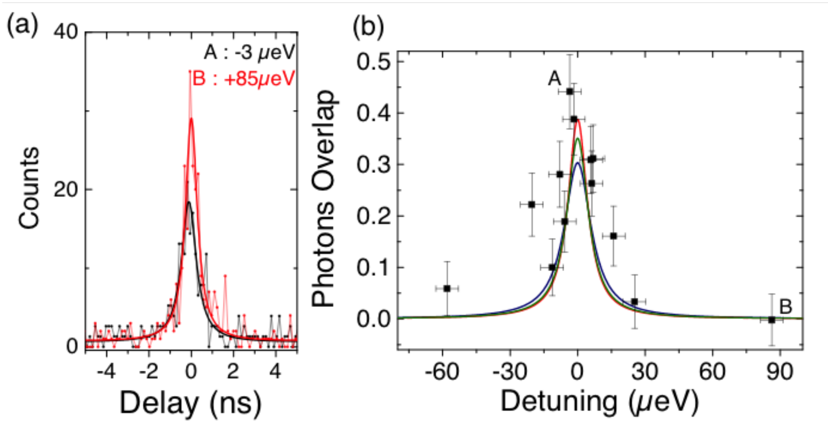

FIGURE 1: (a) Correlation histograms of two-photon interferences from QD1 and QD2 for a relative detuning of -3 μeV (black line) and for 85 μeV (red line). (b) Two-photon overlap as a function of detuning between QD1 and QD2. Solid lines are theoretical results from our model.

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Detector-device-independent quantum key distribution

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The security of quantum key distribution (QKD) depends only on the principles of quantum physics and can be proven information-theoretically secure. However, one still has to be prudent about potential side-channel attacks in the practical implementation that may lead to security failures. For example, it has been shown that with detector blinding techniques, it is possible to remotely hack the measurement unit of some QKD systems [1]. Although it is possible to implement appropriate countermeasures for specific attacks, one may be wary that the adversary could devise new detector control strategies, unforeseen by the users.

To prevent all known and yet-to-be-discovered detector side-channel attacks, a measurement-device-independent QKD (mdiQKD) protocol was proposed [2]. In this scheme, Alice and Bob each randomly prepare one of the four Bennett Brassard (BB84) states and send it to a third party, Charlie, whose role is to introduce entanglement between Alice and Bob via a Bell-state measurement (BSM). Alice and Bob do not have to trust Charlie since any other non-entangling measurement would necessarily introduce some noise between them. Unfortunately, mdiQKD possesses many drawbacks. Firstly, the achievable secure key rates (SKR) are significantly lower compared to conventional prepare and measure (P&M) QKD systems [3, 4]. This is mainly because a two-photon BSM relies on coincidence detections, which sets stringent requirements on the detector efficiency. Another factor is that a two-photon BSM implemented with linear optics is at most 50% efficient and, when using WCSs, the results from one of the bases cannot be used for the raw-key generation due to an inherent 25% error rate [5, 6]. Furthermore, the resource overhead in the finite-key scenario [7] is significantly larger compared to common P&M schemes [4, 8]. Finally, the technological complexity of mdiQKD is greater due to the use of two-photon interference, requiring both photons to be indistinguishable in all degrees of freedom (DOFs) : temporal, polarization and frequency.

We have recently proposed a QKD scheme that overcomes the aforementioned limitations but is still secure against all detector side-channel attacks [9]. This bridges the gap between the superior performance and practicality of P&M QKD schemes and the enhanced security offered by mdiQKD. Our scheme, referred to as detector- device-independent QKD (ddiQKD), essentially follows the idea of mdiQKD, however, instead of encoding separate qubits into two independent photons, we exploit the concept of a two-qubit single-photon (TQSP). This scheme has the following advantages : (1) it requires only single-photon interference, (2) the linear-optical BSM is 10% efficient [10], (3) the secret key rate scales linearly with the SPD detection efficiency and (4) it is expected that in the finite-key scenario the minimum classical post-processing size is similar to that of P&M QKD schemes.

In summary, the ddiQKD protocol overcomes the main disadvantages of the mdiQKD protocol whilst offering the same level of security. Here we present the main concepts of the protocol followed by a proof-of-concept experiment carried out with a heralded single photon source. We then go on to demonstrate the implementation of ddiQKD using a platform capable of high speed operation in real-time using state of the art low-noise In-GaAs/InP detectors ideal for long distance QKD.

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Entanglement-based, wavelength division multiplexed, quantum cryptography link

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Granting information privacy is of crucial importance in our society, notably in fiber communication networks. Quantum cryptography provides a unique means to establish, at remote locations, identical strings of genuine random bits, with a level of secrecy unattainable using classical resources [1]. However, several constraints, such as non-optimized photon number statistics and resources, detectors noise, and optical losses, currently limit the performances in terms of both achievable secret key rates and distances. We circumvent those issues by combining fundamental and off-the-shelves technological resources [2]. We distribute high-quality bipartite photonic entanglement [3] over a 150 km fiber link and exploit a wavelength demultiplexing strategy implemented at the end-user locations. We show how secret key rates scale linearly with the number of employed telecommunication channels, with total bitrates reaching $\sim$ 38 kHz at 0 km and $\sim$ 9 Hz at 150 km. Thanks to its potential of scalability and compliance with device-independent strategies, our system is ready for real quantum applications. In the following, Fig. 1 presents the experimental setup, Fig. 2 the demultiplexing strategy, and Fig. 3 the main results.

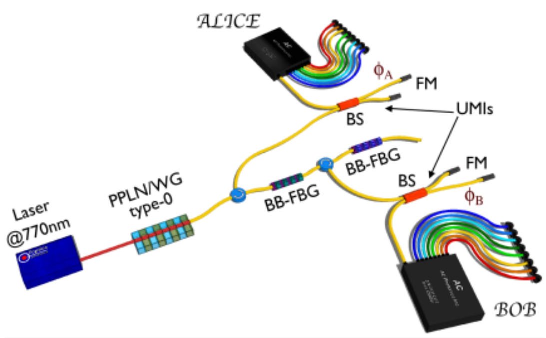

FIGURE 1. Experimental setup. A periodically poled lithium niobate waveguide (PPLN/WG) pumped by a laser at 770 nm emits pairs of energy-time entangled photons in the telecom band via the process of spontaneous parametric down-conversion (SPDC). The quasi-phase matched SPDC spectrum engineered towards reaching the broadest possible bandwidth ($\sim$ 50 nm $\leftrightarrow$ 6THz) around 1540 nm. The pairs of photon are analysed using fully fibered interferometers (UMIs) made of 50/50 couplers (BS) and Faraday Mirrors (FM). The raw bitrates are recorded after the twins photon are split in pairs of complementary telecommunication channels with dense wavelength divion multiplexer (DWDM) employed and set in such a way that they are symmetrical apart from the spectrum degeneracy.

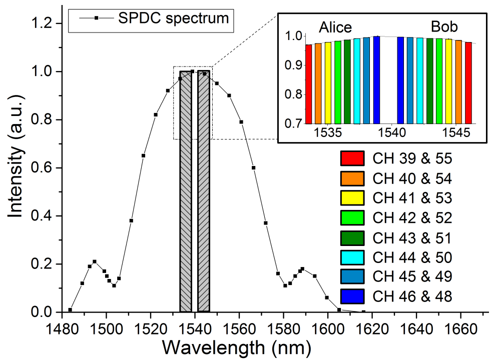

FIGURE 2. Spontaneous parametric down-conversion spectrum out of the PPLN/WG divided in pairs of standard telecommunication channels (ITU).

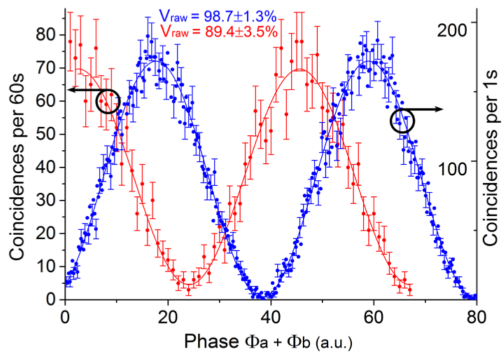

FIGURE 3. 2-photon interference as a function of the sum of the user's interferomters phases for 0 km and 150 km

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Hiding information in the quantum noise of a photograph : Perfectly secure steganography

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Steganography aims at hiding information within a cover medium, which nowadays is often a digital photograph. An information-theoretically secure steganographic protocol based solely on mathematical reasoning has not yet been demonstrated. Here, we show how using a physical aspect of the photographs, namely quantum noise (shot noise), designing a provably secure protocol becomes trivial. This implies that, on a fundamental level, it is impossible to discriminate a private communication from an exchange of photographs. We illustrate the concepts with a proof-of-principle experiment, highlighting some of the practical challenges faced when using physical arguments in a security proof.

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Quantum Fingerprinting with Coherent States for Multiple Clients

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Communication complexity studies the amount of communication required by separate parties to jointly compute a task. A general communication complexity is modeled as having *Client1* and *Client2* who receive input(s) $x, y \in \{0,1\}$ respectively. Their task is to jointly compute a binary function $f(x,y)$ with minimum inter communication as possible. Our work focuses on simultaneous message passing (SMP)[1] model (Figure 1) involving a Referee and two servers Alice(A) and Bob(B) who have multiple (l) clients connected to them. Each client receives an n bit input and every client from server A wants to check for equality with the input of some other client in server B. The communication between the server and Referee is limited by k channels. During the protocol run, the only communication that is possible is client→server and server→referee. Direct communications between client→client or server→server is forbidden. The function can trivially be computed if the all the clients send their n bit inputs to the server and server relays it to the Referee via the k channels. But this would involve high communication costs if the input size is big. With the objective of minimizing this cost, the players can instead make a fingerprint of their inputs which would be considerably smaller in size which achieves the same task of computing $f(x,y)$ with a small error probability ϵ.

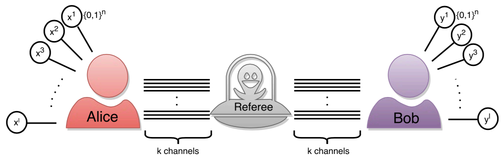

FIGURE 1. l Clients connected to servers Alice and Bob who communicate to the Referee via k cables

We first talk about the best *classical fingerprinting protocol* [2]. The clients create the fingerprint of length $2\sqrt{n}$ + O(1) bits and send them to the servers who eventually sends it to the referee. The referee compares it with the fingerprint from a client of the other server and returns the result. One such equality succeeds with an error probability $\epsilon = 0.25$. Next we define the *quantum fingerprinting protocol* with qubits. The objective is to look at the protocol from implementation point of view. Ideally, the use of single photons for implementing the quantum fingerprint is a highly challenging task because of the limitation in preparing single photon qubits with high accuracy. Instead we use coherent states the prepare quantum fingerprints. Since our model involves multiple clients with multiple equalities, we propose a novel idea of using frequency multiplexing of the coherent fingerprinting states with k channels, to have a gain in communication costs compared to the best classical protocol.
We also talk about the communication resources involved in the protocol, *Transmitted Information, Energy* and *Time taken*, and compare them in the classical and quantum scenarios.

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Squeezing at a telecom wavelength, a full waveguide approach

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Continuous variables (CV) quantum optics uses squeezed light as an essential resource to realize CV protocols for quantum communication, unconditional quantum teleportation, and one-way quantum computing [1]. In most of experiments, generation of squeezing is ensured by spontaneous parametric down-conversion, while detection is achieved by homodyne detection after linear-optical manipulation of the states. So far, squeezing experiments have been reported at both visible and telecom wavelengths [2], but most of them are based on free-space configurations. However, free-space approaches remain hardly scalable, making it difficult the implementation of CV quantum information protocols in existing fibre based communication networks.

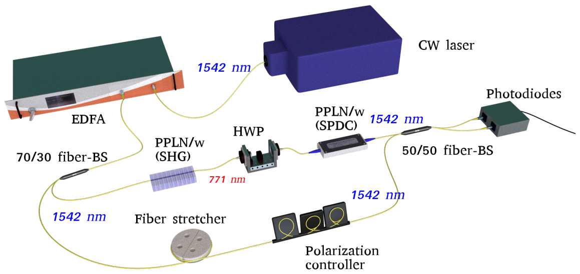

FIGURE 1: Experimental setup. EDFA, erbium-doped fiber amplifier ; PPLN/w, periodically poled lithium niobate waveguide ; SHG, second harmonic generation ; SPDC, spontaneous parametric downconversion

To overcome this drawback, we demonstrate in this work the feasibility of a fully guided-wave realization of a squeezing experiment at telecom wavelength fully compatible with existing telecom fibre networks. The setup is depicted in Fig.1. A 1542 nm CW laser is amplified by an EDFA, split into two arms using a 70/30 fibre-BS. In the upper arm, the laser is frequency doubled to 771 nm in a single pass periodically poled lithium niobate waveguide (PPLN/w). Light at 771 nm is fibre coupled and sent to a ridge PPLN/w to generate squeezed light at 1542 nm, again in a single pass configuration. The light is fibre coupled and interferes with the local oscillator (LO) coming from the second arm at a 50/50 fibre-BS. Note that the fibre-BS automatically ensures perfect spatial mode overlap between squeezed light and the LO, which is usually a critical task in free-space configuration. Finally, the phase of the LO is tuned with a fibre stretcher.

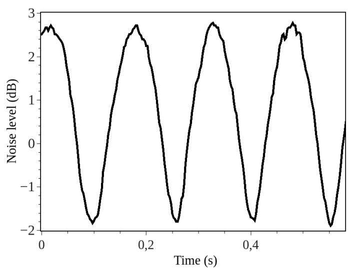

FIGURE 2: Normalized noise variances at 2 MHz of squeezed vacuum state as a function of the local oscillator phase.

As a result, we detect 1.83 dB of squeezing for an overall detection efficiency of 52%, see Fig.2, demonstrating the feasibility of our approach. Furthermore, the compactness of the experiment compared to free-space configurations is a significant step toward implementing out-of-the-lab CV quantum communication. We believe that this work stands as an interesting realization for real applications as well as for "do-it-yourself" experiments.

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Unidimensional continuous-variable quantum key distribution

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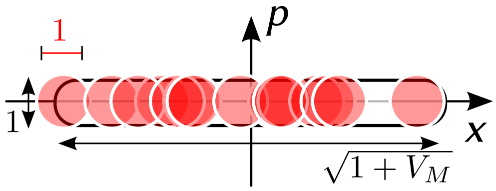
In [1], we propose a continuous-variable (CV) quantum key distribution (QKD) protocol-based on the Gaussian modulation of a single quadrature of coherent states of light. This simplification of the symmetric GG02 [2] protocol has two aims, one experimental, and one theoretical.

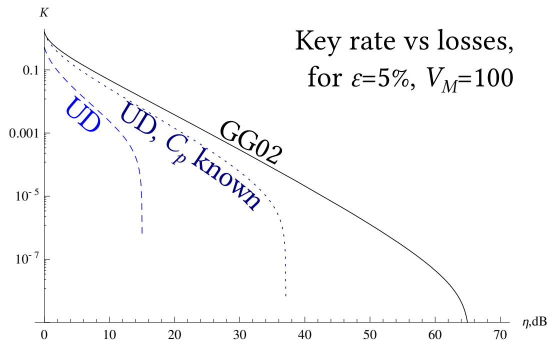
Experimally, the protocol assymmetry allows Alice to use one modulator (e.g. an amplitude modulator) instead of two and therfore reduce the price of her apparatus. Furthermore, the amplitude modulator used in a symmetric CV QKD apparatus needs to have a strong extinction ratio, in order to avoid creating a "hole" in the center of the Gaussian probability distribution. On the other hand, our simple 1D amplitude modulation does not have this need, and the use of a more standard (and cheaper) modulator becomes possible.

On a theoretical side, this protocol is the minimal Gaussian CV protocol, and plays a role similar to B92 for discrete variables. The analysis of its security shows that one can obtain reasonable security rate, even if its whole covariance matrix cannot be measured.

The price paid in term of rate, range and tolerable excess noise stays reasonable, and an experimental implementation of this protocol seems realistic. This price is mainly due to the impossibility for Alice and Bob to reconstruct the whole covariance matrix.



Schematic representation of Alice modulation in phase-space.



Keyrate of the protocol (UD), for a 5% excess noise, compared to the protocol with a fully known covaraince matrix and the symmetric GG02 protocol

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Quantum Information Foundations - FOUND

Amplification and noise from voltage-biased Josephson junctions

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The readout of superconducting qubits and other quantum devices operating at microwave frequencies requires amplifiers combining noise close to the quantum limit[1], high gain, large bandwidth, and sufficient dynamic range[2]. Josephson parametric amplifiers using Josephson junctions in the 0-voltage state, driven by a large microwave signals, begin to perform sufficiently well in all 4 of these aspects to be of practical use, but remain difficult to optimize and use. Recent experiments with superconducting circuits consisting of a DC voltage-biased Josephson junction in series with a resonator, showed that a tunneling Cooper pair can emit one or several photons with a total energy of 2e times the applied voltage[3]. We present microwave reflection measurements on this device in [3], indicating that amplification is possible with a simple DC voltage-biased Josephson junction. We compare these measurements with the noise power emitted by the junction [3] and show that, for low Josephson energy, transmission and noise emission can be explained within the framework of P(E) theory of inelastic Cooper pair tunneling. Combined with a theoretical model, our results indicate that voltage-biased Josephson junctions might be useful for amplification near the quantum limit, offering simpler design and a different trade-off between gain, bandwidth and dynamic range, which could be advantageous in some situations.

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Deformed Asymmetric Phase-Covariant Quantum Cloning

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In this work, we use the mathematical formalism derived from the Kaniadakis entropy [1] to build a generalized form of the optimal asymmetric $1 \to 2$ phase-covariant quantum cloning. Recently, we used [2] the mathematical structures derived from Tsallis and Naudts entropies [3, 4] to realize this generalization. The Fidelities obtained from these three deformed cases are compared. The symmetric quantum clonning is considerd. The influence of the nonextensivity on the perfection of clones is graphically illustrated for different values of entanglement parameter θ and nonextensive parameter.

We consider the input state in generalized formulation of asymmetric phase-covariant quantum cloning$|\psi\rangle_a^{in} = \frac{1}{\sqrt{2}}\left(|0\rangle_a + e^{i\phi}|1\rangle_a\right)$

The generalized asymmetric phase-covariant cloning machine is analyzed by the following transformation :

$$|0\rangle_a |0\rangle_b |0\rangle_c \to \frac{1}{\sqrt{2}}\left[|000\rangle + G(q)\left(\cos_q(\theta)|01\rangle + \sin_q(\theta)|10\rangle\right)|1\rangle\right]$$
$$|1\rangle_a |0\rangle_b |0\rangle_c \to \frac{1}{\sqrt{2}}\left[|111\rangle + G(q)\left(\cos_q(\theta)|10\rangle + \sin_q(\theta)|01\rangle\right)|0\rangle\right]$$

where $G(q) = 1$ in the standard statistics case and $G(q) = \xi_q$ in the deformed statistics cases. Here, for the different deformed statistics, the function ξ_q takes different values. We find $\xi_q = \sqrt{\frac{1}{exp_q(1-q)\theta^2}}$ for Tsallis case, where $exp_q(i\theta) = e_q(i\theta) = [1 + i(1-q)\theta]^{\frac{1}{1-q}}$. And $\xi_q = \sqrt{\frac{1}{exp_q\left(\frac{q}{1+q}\theta^2\right)}}$ for the Naudts case, where $exp_q(\theta) = e_q(\theta) = \left[1 + \frac{q}{1+q}\theta\right]_+^{\frac{1}{q}}$, $[x]_+ = max\{0, x\}$. And $\xi_q = \frac{1}{\sqrt{R_+R_-}}$ for Kaniadakis case, where $R_\pm = \left(\sqrt{1-k^2\theta^2} \pm ik\theta\right)^{1/k}$ and $exp_k(x) = \left(\sqrt{1+k^2x^2} + kx\right)^{\frac{1}{k}}$.

If we clone the state $|\psi\rangle_a^{in}$, we obtain : $|\psi\rangle_a^{in}|0\rangle_b|0\rangle_c \longmapsto |\psi\rangle_{abc}^{out}$. After the copying procedure, the density operator $\rho_{ab}^{out} = Tr_c |\psi\rangle_{abc}^{out}\langle\psi|_{abc}^{out}$ describes the state of the original-copy.

A comparison of these deformed statisticsis is realized through the fidelity $F = \left[Tr\sqrt{\left(\sqrt{\rho^{in}}\rho^{out}\sqrt{\rho^{in}}\right)}\right]^2$. The obtained results shows that, the entanglement varies with the intrinsic properties of the system and consequently it is not preserved, but it can be controlled by the nonextensive parameter.

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[4] Jan Naudts. arXiv :cond-mat/0203489v1 [cond-mat.stat-mech]

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Encoding discrete quantum information in continuous variables : A modular variables approach

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

In the present talk, we use modular variables to show that, in a number of relevant protocols of quantum information and for the realization of fundamental tests of quantum mechanics, it is possible to loosen the requirements on the encoded subspace, facilitating their experimental implementation [2, 3]. Thereby, modular variables are defined by dividing the spectrum of two conjugate observables into a discrete and a modular part, respectively, allowing for the definition of a new basis that is characterised solely by the bounded values of the corresponding modular eigenvalues. In particular, by considering protocols that involve measurements of appropriately chosen modular observables, we permit to extend the equivalence between the continuous analogous of the Pauli matrices to a more general class of qubit encodings in continuous variables.

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

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Fast polarization switch and polarization entangled photon pair source optimization for a loophole-free violation of Bell's inequality

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Experimental violation of the Bell's inequality [1] demonstrates that local realistic can not definitive describe the world. Polarization entangled photon pairs are an appealing resource for such inequality experiments because of their properties: easily transmitted, little interaction with environment, easy manipulation of the polarization degree of freedom.

Until now, there has not been yet a loophole-free experiment based on photon pairs violating the bell inequality. The detection, freedom-of-choice, and locality loopholes should be closed at same time for the violation. Giustina et al. [2] and Christensen et al. [3] closed the detection loophole in their respectively experiments. Recently, a loophole free experiment on soild-state qubits was conducted and likely violated the Bell inequality by about two standard-deviations [4].

We generate polarization entanglement by Sagnac-like geometry [5] in type-II parametric down-conversion (SPDC) process. Periodically poled KTP crystal is pumped by 405nm CW laser in two opposite directions. The generated photon pairs at 810 nm have adjustable degree of entanglement in polarization. We plan to close the detection loophole by using two high detection efficiency (> 95 %) transition-edge sensors (TES) [6]. Pair generation, basis implementation and photon detection events must be space-like separated to close the locality loophole. To fulfill this condition while reducing the minimal required space-like separation, we reduce the basis implementation time and detection time. A switch capable of switching between measurement bases within tens of nanoseconds was designed and will be eventually controlled by a quantum random number generator.

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Measurement dependence and limited detection nonlocality

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Quantum nonlocality stands as a resource for device independent quantum information processing (DIQIP) [1]. It finds repercussions in applications such as, among others, quantum key distribution [2] and generation of randomness [3]. In this work, we investigate two different approaches to attest nonlocality. First we follow the assumption of limited measurement dependence, *i.e.*, that the measurement settings used in Bell inequality tests or DIQIP are partially influenced by the source of entangled particles and/or by an adversary. Then, we introduce the intermediate assumption of limited detection efficiency, that is, in each run of the experiment, the overall detection efficiency is lower bounded by $\eta_{min} > 0$. Hence, in an adversarial scenario, the adversaries have arbitrary large but not full control over the inefficiencies. We analyse the set of possible correlations that fulfil Measurement Dependence/Limited Detection Locality (MDL/LDL) and show that they necessarily satisfy some linear Bell-like inequalities. In both scenari, quantum theory predicts the violation of such inequalities for $l > 0$ in the first case, and $\eta_{min} > 0$ in the other. We validate these assumptions experimentally via a twin-photon implementation in which two users are provided each with one photon out of a partially entangled pair. On one hand, we show with the first inequality that the measurement independence assumption can be widely relaxed while still demonstrating quantum nonlocality. On the other hand with the second inequality, assuming the switches between the measurement bases are not fully controlled by an adversary, nor by hypothetical local variables, we reveal the nonlocality of the established correlations despite a low overall detection efficiency. Note that all the theoritical details associated with MDL/LDL can be found in [4]/[5]. Moreover, the experimental violation of these inegalities are reported in [6]/[5].

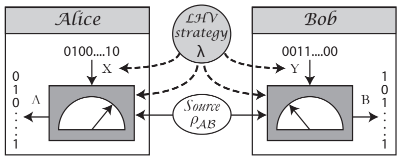

FIGURE 1. Standard quantum correlation measurement scheme, in the presence of a local hidden variable (LHV) strategy. Two users, Alice ($\mathcal{A}$) and Bob ($\mathcal{B}$), each have a measurement apparatus. These devices each take a binary input (x,y) and return a binary output (a,b). They can also be provided with a hidden common variable, λ, to mimic a non-local quantum resource. Note that the LHV can influence the input choices of both Alice and Bob. This scenario is called measurement dependent locality.

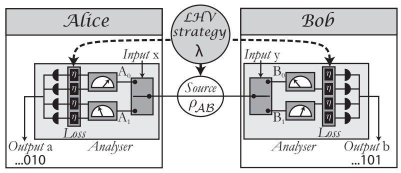

FIGURE 2. Two boxes receive each a particle, emitted by a common source. They are given inputs x and y, which we depict here as the setting of an active switch, and return outputs a and b, respectively. There is the possibility for non-detection events, in which case the corresponding output variable takes the value $\varnothing$. Since these losses can be seen as happening inside the box, they can depend on the inputs x and y, respectively. We analyze the limited detection local case of this scenario, meaning that a local hidden variable λ not only fully describes the state of the particle, but can also influence whether or not a non-detection event occurs.

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Modeling Leggett-Garg inequality violation

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The Leggett-Garg inequality is a widely used test of the "quantumness" of a system, and involves correlations between measurements realized at different times. According to its widespread interpretation, a violation of the Legget-Garg inequality disproofs macroscopic realism and non-invasiveness. Nevertheless, recent results point out that macroscopic realism is a model dependent notion and that one should always be able to attribute to invasiveness a violation of a Legget-Garg inequality. This opens some natural questions : how to provide such an attribution in a systematic way ? How can apparent macroscopic realism violation be recast into a dimensional independent invasiveness model ? The present work answers these questions by introducing an operational model where the effects of invasiveness are controllable through a parameter associated to what is called the *measurability* of the physical system. Such a parameter leads to different generalized measurements that can be associated to the dimensionality of a system, to measurement errors or to back action.

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Novel Tsirelson-like bounds

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Bell tests have received a lot of attention over the recent years. In such experiments two or more parties perform measurements on a shared resource (e.g. shared randomness, entangled particles, etc.) and the correlations between them vary according to nature of the resources they have. This was first shown in 1964 by John Bell, who established that some quantum correlations cannot be reproduced by "classical" models, i.e. local hidden variable models [1].

In the device-independent approach, the apparatuses of the Bell experiment are considered as "black boxes", and the only object studied is the probability distribution that the parties estimate at the end. For two parties this is $p = \{P(ab|xy)\}$, where $P(ab|xy)$ is the joint probability that the first user, Alice, obtains an output a from her black box given that she had chosen input x and that the second user, Bob, obtains an output b given that he had chosen input y. If these correlations violate what is called a Bell inequality, they are nonlocal.

One can also represent the situation geometrically and distinguish different sets for p, according to its compatibility with the nature of the resources shared by the parties. Particular attention has been given to the set $\mathcal{Q}$ of quantum correlations (i.e. correlations obtained through quantum measurements on a quantum state). It remains an open problem to recover this set from a series of principles which would be operationally motivated (see for instance [2]). And beyond this question, there is not even an efficient characterization of $\mathcal{Q}$ on the mathematical level, although an important step was achieved in [3], which introduced the so-called NPA hierarchy. Note that another advance was made in [4] where new analytical bounds were derived to constrain $\mathcal{Q}$.

In that context, it is thus highly desirable to establish the quantum bounds of Bell inequalities, also called Tsirelson bounds, in various scenarios. Although this has been achieved numerically for a number of inequalities via the NPA hierarchy, it was done analytically only in very few cases. The motivation for this problem is also practical, since the study of properties of Bell inequalities is present at the heart of quantum information processing, through various device-independent protocols such as randomness expansion or self-testing.

In our work, we construct a class of bipartite Bell inequalities with an arbitrary number of inputs m and an arbitrary number of outputs d, and we analytically provide their Tsirelson bound. Our proof relies on the sum-of-squares (SOS) decompositions of the shifted Bell operator, which were explored for instance in [5]. Furthermore, we are able to prove that the maximal quantum violation is attained by the maximally entangled state. This last feature is to our knowledge a rare property, and contributes to one of Nicolas Gisin's questions formulated in [6] : "Why are almost all kown Bell inequalities for more than two outcomes maximally violated by states that are not maximally entangled ?". Our proof also paves the way to using our inequalities in device-independent protocols.

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Quantum Protocols within Spekkens' Toy Model

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Quantum theory is known to provide advantages with respect to classical information processing tasks and protocols. In broader terms, it can even be argued that it provides a whole new framework for information processing tasks, where rules are different and gains are often higher than in their classical counterparts. Although the first quantum protocols date back to the early 80s, there is not yet a communal agreement regarding which features of quantum theory are truly responsible for these improvements. Among the many candidates Bell non-locality and contextuality are often considered as the 'specifically quantum features' which are responsible for most of the advantages. In the given project we show that many quantum protocols – such as blind and verified computation, secret sharing, and error correcting codes – can be translated and run on a very simple and fully classical model known as the toy model [1]. Beside the foundational interest, this work relates also more applied consideration as it helps to pinpoint the core features behind the existence of these protocols. In this respect the toy model, and various extensions of it, are related to physically motivated restrictions of quantum theory such as Gaussian quantum optics where toy protocols can be performed [2].

The toy model is a local, realist, and classical physical theory which reproduces many properties of quantum theory such as the noncommutativity of measurements, interference, the multiplicity of convex decompositions of a mixed state, no cloning, remote steering, teleportation, and many others [1]. However, due to its local and classical nature the toy model cannot reproduce any non-locality or contextuality. Therefore, while translating quantum protocols to the toy model provides no claims with respect to quantum speeds up (the toy model is fully classically simulable), it still directly implies that these protocols do not relay on non-locality, but rather make use of some other property.

Starting from the work of Pusey who developed a notation for the toy model reminiscent of the quantum stabilizer formalism for qubits [3], we expand the formalism by developing a framework where computations based on stabilizer states can be more easily treated. This allowed us to prove the following three results. Firstly, we proved the existence of a model for universal toy computation based on single system measurements and toy graph states which we called the 'measurement based toy computation' model, highlighting its similarity with measurement based quantum computation model(MBQC) [4]. This in turn allowed us to translate to the toy model the protocol for blind and verified computation defined for MBQC, firstly presented in [5]. Secondly, we proved that to any quantum stabilizer error correcting code there exists a toy error correcting code bearing the same distance and structure. We further showed the existence of a no-deletion theorem and showed that any k-threshold secret sharing code is also an error correcting code just as in the quantum case. Finally, we affirmatively answered Spekkens conjecture regarding the impossibility of perfect and imperfect bit-commitment schemes in the toy model.

Our results firstly confirmed the intuition that bit commitment is forbidden in theories that present purifications ; they further showed that error correction is possible for a local theory which features a no-cloning theorem and that the protocol does not need to invoke non-locality. But stronger and more important are the implications for the blind and verified protocol. Here, the result strongly suggests that the ability to implement the verification protocol is rather based on the steering properties of the toy model than any form of Bell non-locality. Since up to date known quantum verification schemes either explicitly use non-locality, or they are conjectured to require it in order to work, our result suggests instead that steering properties to suffice. This claim can be further tested in an experimental set up by using local subtheories of quantum mechanics.

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IQFA 2015: Quantum walk mixing using hidden variables

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Quantum walks on graphs [1] are an extension of random walks to the quantum domain. Towards mixing, they can seemingly provide a quadratic speedup compared to reversible classical random walks. On the other hand, lifted random walks, as proposed by Diaconis et al. [2], are a non-quantum extension proven to deliver the same speedup [3]. However, the construction of lifted walks makes explicit use of multicommodity flows, rendering their construction **NP**-hard. The gain of using a quantum algorithm for mixing would thus strongly rely on the complexity of its construction; however so far not even an existence proof exists for quantum walks with mixing times quadratically improving the standard random walk, except for very specific graphs. The end goal of our research is hence to elucidate the key element(s) that provide acceleration in quantum walks, and compare them to lifted walks. In this contribution we explore the possibilities of approximating the quantum walk dynamics, or at least their mixing behaviour, by using a classical, local scheme, comparable to a lifted random walk. Amongst other questions, we focus on whether nonlocal features contribute to the speedup attained by quantum walks, and if so to what extent.

Inherent to the nature of quantum evolution are its nonlocal features. It is such features that introduce Bell-like inequalities, and make it generally impossible to construct a local realistic theory, correctly predicting the dynamics of a quantum system. When analysing the problem of quantum walk mixing on a graph however, we show that the setting can be greatly restricted, and hence its main difficulties bypassed. By only demanding to approximate the mixing properties of the quantum walk, the dynamics are restricted to homogeneous, discrete-time evolution in a fixed finite-dimensional basis, in which the initial state is diagonal. This circumvents issues of a similar goal as presented by e.g. Aaronson [4]. The nonlocal features only have to be incorporated to the extent that they influence the mixing behaviour. In addition we use the results of Aharonov et al. [1] (amplification lemma) and Richter [5]; they show it is beneficious - and in general, necessary - towards mixing to perform intermediate measurements on the quantum walk, thus only allowing a limited amount of “coherent” timesteps. To approximate the quantum walk mixing dynamics in a classical way, this implies that only a limited amount of timesteps in the quantum domain have to be simulated. As a further remark, we underline the asymptotic behaviour of quantum walk mixing, i.e. its quadratic speedup, has been proven to be attainable using a classical lifted walk, even though its construction is **NP**-hard.

Elaborating on the above observations, we show that in some specific examples it is possible to exactly simulate the quantum walk dynamics, and hence its mixing properties, using a classical, local random walk with additional hidden states. This shows that the nonlocal features, to the extent that they influence the mixing behaviour, can at least in some cases be mimicked using localized hidden states. This result hints towards narrowing the gap between quantum walks and classical schemes when it comes down to mixing. Using this observation as a starting point, we aim to find more general results regarding existence and construction of classical schemes approximating the quantum walk mixing behaviour.

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Transition-edge sensor and signal discrimination optimisation for a loophole-free violation of Bell's inequality

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A loophole-free violation of Bell's inequality implies the rejection of local realistic theories [1]. Until recently, technological limitations have prevented the simultaneous closing of all experimental loopholes. While such violation has likely been demonstrated using spin-entangled NV-centres [2], it has not been achieved with photons. Polarisation-entangled photon pairs are an appealing resource since they are easily transmitted, have little interaction with environment, and can be produced at high rates. We use polarisation-entangled photon pairs and plan to progressively close all loopholes.

By efficient collection of a spontaneous parametric down-conversion (SPDC) source that generates nonmaximally entangled states [3], and the use of transition-edge sensors (TES), we achieve an overall collection efficiency larger than 66.7% [4]. This allows us to close the detection loophole as previously demonstrated by Giustina et al. [5] and Christensen et al. [6].

The photon pair source is based on a periodically poled KTP crystal, pumped by 405 nm light in two opposite directions. The down-converted, wavelength-degenerate photon pairs are coupled in a Sagnac-like configuration, allowing us to adjust the degree of polarisation entanglement [3].

The detection and pair generation events are kept space-like seperated to close the locality loophole. This imposes a time limit on the detection event. Large detector jitter times increase the coincidence windows being used to identify photon pairs. This results in a larger minimum space-like seperation between source and detector. Since transmission losses increase with source-detector seperation, this situation is undesirable. We use low input inductance SQUIDS that inductively couple to the TES, providing higher bandwidth voltage readout, to reduce jitter to tens of nanoseconds [7]. The TES and SQUID operating parameters are optimised for both efficiency and timing precision, to simultaneously close the detection and locality loopholes. Leading edge and peak discrimination methods are compared to implement the best triggering strategy on the SQUID output pulses with our electronics.

Another factor that affects the required space-like seperation is the duration of switching between polarisation bases. We develop fast polarisation switches that reduce the switching time to tens of nanoseconds. Quantum random number generators will be used to determine the basis choices to close the freedom-of-choice loophole.

The basis choice, implementation and detection events will be sufficiently space-like seperated to ensure that the locality loophole is closed. Finally, all loopholes will be closed simultaneously.

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Optimal GHZ Paradox for Three Qubits

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Quatum nonlocality as a valuable resource is of vital importance in quantum information processing. The characterization of the resource has been extensively investigated mainly for pure states, while relatively less is know for mixed states. Here we will prove the existence of the optimal GHZ paradox by using a novel and simple method to extract an optimal state that can saturate the trade-off relation between quantum nonlocality and the state purity. In this paradox, the logical inequality which is formulated by the GHZ-typed event probabilities can be violated maximally by the optimal state for any fixed amount of purity (or mixedness). Moreover, the optimal state can be described as a standard GHZ state suffering flipped color noise. The maximal amount of noise that the optimal state can resist is 50%. We suggest our result to be a step toward deeper understanding of the role played by the AVN proof of quantum nonlocality as a useful physical resource.

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Quantum Information Storage - QuIS

Coherent Spin Control at the quantum level in an ensemble based optical memory

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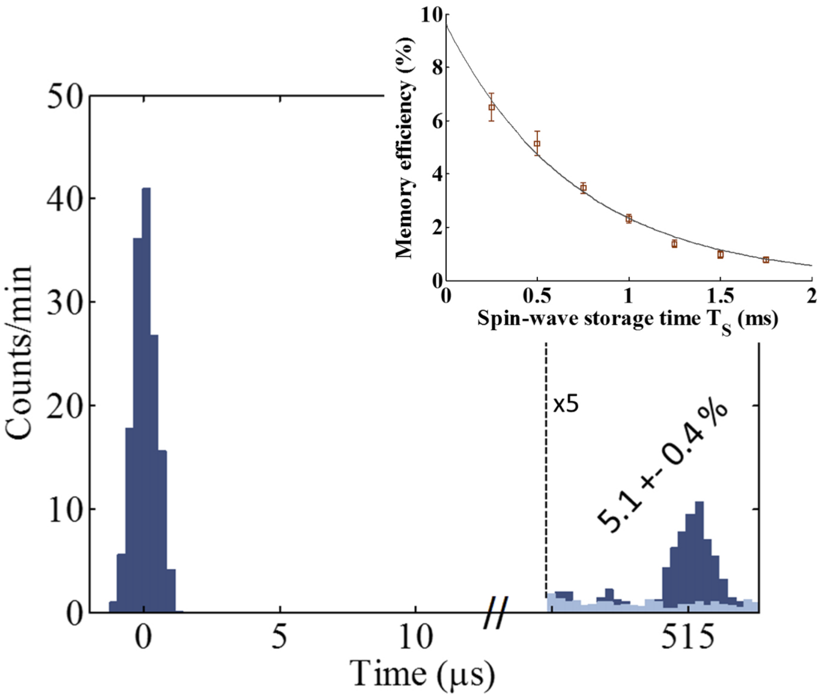
Efficient and long-lived memories are key devices in the development of long-distance quantum communication. DLCZ-type quantum repeaters, for instance, require the possibility to store and retrieve a state on demand. Long-lived storage can be realized by storing the light as spin excitations. However, so far only strong classical pulses had been stored as spin waves in solid-state memories (eg. [1]). Storage of light at the single photon level turns out to be very challenging due to intrinsic photon noise [2]. Here we show the first storage and retrieval of coherent states of light containing an average number of photons of the order of 1 in a solid-state memory, for durations of the order of one millisecond [3]. Similar results were obtained in parallel by Gündogan et al. [4].

We use the AFC spin-wave technique for our rare-earth-ion doped crystal memory of Eu^{3+} :Y_2SiO_5. In order to avoid spin dephasing during the storage in the spin state, we use radio-frequency pi-rephasing pulses, as used in [1]. We also show the greater robustness against errors of the XY-4 sequence compared to the XX sequence.

This way, pulses containing two photons in average have been stored for 1 ms with a storage efficiency of 2.3 % (see figure) and a signal to noise ratio of 7 [3]. Then, we have also performed the storage of five temporal modes of polarization qubits containing down to 0.8 photons on average, revealing the multimode capacity at the quantum level of our device [5].



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Field estimation from stabilizer syndrome measurements

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In the context of measurement-based quantum computation (MBQC) a way of maintaining the coherence of a *graph state* is to measure its stabilizer operators (a.k.a. *correlators*). Aside from performing quantum error correction (QEC), it is possible to exploit the information gained from these measurements to characterize a coherent source of errors ; that is, to determine all the parameters of an *error channel* that applies a fixed –but unknown– unitary operation to the physical qubits. Such a channel is generated e.g. by local stray fields that act on the qubits. We study the case in which each qubit of a given *graph state* may see a different error channel ; and we focus on channels given by a rotation on the Bloch sphere around either the $\hat{x}$, $\hat{y}$ or $\hat{z}$ axis, for which analytical results can be given in a compact form. The possibility of reconstructing the channel at all vertices depends non-trivially on the topology of the graph state. We prove via perturbation methods and Monte Carlo simulations that the reconstruction process is robust, that is, small uncertainties in the measured values are not amplified.

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Quantum Metrology - QMET

Adaptive estimation of a fluctuating phase

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Estimating a phase imposed on an optical beam is the basis of quantum metrology. A problem of practical importance is the estimation of a phase which varies in time, for example for gravitational wave detection. It has been shown that the lower bound on the mean square error (MSE) of measuring a varying phase with Gaussian statistics and a power law spectrum $1/\omega^p$ scales as $N^{-2(p-1)/(p+1)}$, where N is the mean photon flux (photons per second) [1]. This lower bound can be achieved by sampling with a regularly spaced sequence of pulses, each of which is measured by a canonical phase measurement [1].

The aim of this theoretical work is to find the MSE in estimation of a time varying phase using adaptive (rather than canonical) measurements. In adaptive measurements the phase of the local oscillator is continuously changed in time to follow an estimate of the phase [2, 3]. Moreover, in this scheme we consider continuous Gaussian fields (rather than a sequence of pulses). For even powers p, the problem simplifies and the MSE can be calculated analytically, whereas for general p we determine the MSE via numerical simulations.

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Boosting Sensitivity of Quantum Probes with Error Correction

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Quantum metrology is one of the thriving quantum technologies that has attracted great attention over the last decade, due to the outstanding enhancements derived from the ability to control physical systems to the limit dictated by quantum mechanics. Common to all of these technologies is the necessity to decouple quantum systems from their environment, while maximizing control. In the context of quantum magnetometry, a single highly coherent probe can be used to measure very weak magnetic fields via Ramsey interferometry, with a sensitivity that scales as $\delta B \propto 1/\sqrt{T \cdot T_2}$ [1, 2], where T is the total experiment time and T_2 is the probe coherence time.

Relaxation imposes a fundamental limit on the sensitivity of state of the art quantum sensors which cannot be overcome by dynamical decoupling. So far, the only way to overcome this is to utilise quantum error correcting codes. When incorporated in sensing protocols, quantum error correction can be used to correct for high frequency noise, as the correction procedure does not depend on the actual shape of the noise spectrum. It therefore provides a powerful way to complement usual refocusing techniques.

The fundamental problem behind quantum error correction-enhanced sensing is the engineering of a many-body Hamiltonian term with strength proportional to the signal to be estimated. This is necessary in order to operate in the logical subspace of the error correcting code, which is protected against to first-order noise processes. Here we propose a superconducting circuit design to sense magnetic fields with a precision that is not relaxation-limited, by means of a two-body Hamiltonian term which arises from a tunable coupler between two off-resonant transmon qubits [3, 4].

Correcting at a sufficiently high rate and gate fidelity can increase the lifetime by several orders of magnitude. This opens up the possibility to perform quantum metrology in a fault-tolerant manner, that is, probing signals at the logical level while fighting general quantum noise induced by the environment as well as by the correction procedure.

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Entanglement-based high-accuracy chromatic dispersion measurements

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Quantum optical metrology enables phase sensitive measurements with a resolution beyond the classical Heisenberg limit. Here, we demonstrate a novel quantum metrology scheme for entanglement-enhanced chromatic dispersion (CD) measurements in short fibres and samples. Besides the expected doubled phase sensitivity, exploiting energy-time and path entanglement allows eliminating the major inconveniences of classical measurements based on white light interferometry (WLI). Our experimental procedure is significantly faster compared to the classical counterpart, and entanglement permits to further exploit a more simplified fitting function. Using these advantages, we measure CD in a 1 m long standard telecom fibre (Corning SMF28e) with an accuracy on top of the state-of-the-art, *i.e.* with an 1.7 times improved accuracy compared to the classical strategy. Interestingly, this advantage is achieved despite using much less light. In addition, we demonstrate a CD measurement in a 6.7 cm long fibre, which is, to our knowledge, the shortest SMF28e fibre length for which CD has been measured.

CD of a sample is related to the second order derivative of the refractive index n by $D(\lambda) = -\frac{\lambda}{c} \cdot \frac{d^2n}{d\lambda^2}$, where λ is the wavelength, and c the speed of light. Many fields in physics require precise knowledge of CD. To name only a few prominent examples, Raman scattering, four-wave mixing, self-phase modulation, supercontinuum generation, and the improvement of telecom networks rely all on CD design and management.

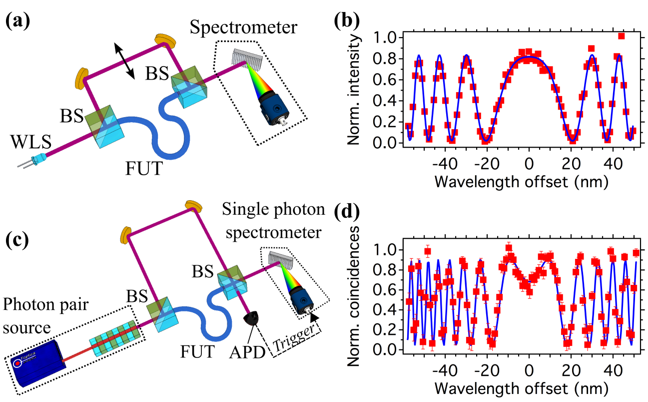

FIGURE 1: (a) Classical WLI setup for CD measurements. WLS : white light source, BS : beam-splitter. (b) Classical results. A wavelength offset of zero corresponds to 1561 nm. (c) Entanglement-based setup. (d) Results in the quantum regime.

Classical measurement

FIGURE 1(a) shows the classical way of measuring CD in a short fibre under test (FUT) using a WLI. CD is inferred by analysing the interference fringes in the spectral domain at the interferometer output [1]. One of the major inconveniences of this technique is that for every new sample the so-called stationary phase point (SPP) needs to be found by precisely adjusting the length of one interferometer arm. After performing this procedure, we obtain the measurement shown in FIGURE 1(b). Using a third order fit function, we obtain $D = -17.01 \pm 0.10 \frac{\mathrm{ps}}{\mathrm{nm \cdot km}}$ at 1561 nm, which is in good agreement with the manufacturer's specifications, and the related accuracy matches the state-of-the-art [1, 2].

Quantum measurement

The entanglement-based setup is shown in FIGURE 1(c). The classical light source is replaced by an energy-time entangled photon pair source [3] and the interferometer is now fixed in an unbalanced configuration ($\Delta L \gtrsim 7\,\mathrm{cm}$). This allows us to exploit a two-photon $N00N$-state via post-selection in the time domain. An avalanche photo diode (APD) at one interferometer output triggers, upon a detection event, a single photon sensitive spectrometer in order to post-select the desired $N00N$-states. Thanks to energy-time entanglement, the procedure of finding the SPP becomes obsolete, such that we can directly proceed to the measurement of the coincidence spectrogram, which is shown in FIGURE 1(d). We obtain twice as fast interference fringes which reflects the increased phase sensitivity of the quantum strategy. Additionally, as energy-time entanglement also strongly suppresses the dependence on third order derivative terms, data can be fitted using a second order function. We obtain $D = -16.88 \pm 0.06 \frac{\mathrm{ps}}{\mathrm{nm \cdot km}}$ at 1561 nm, which represents a 1.7 times enhanced accuracy compared to the classical strategy, despite using significantly less light. This is explained by both an increased number of observed interference fringes for the same spectral bandwidth, and by a simplified fitting function with fewer free parameters. Thanks to the enhanced sensitivity and accuracy, we measure CD also in a 6.7 cm long fibre, obtaining $D = -15.4 \pm 0.3 \frac{\mathrm{ps}}{\mathrm{nm \cdot km}}$ at 1542 nm. To our knowledge, CD has never been measured in such a short SMF28e fibre with comparable accuracy. We emphasize that our strategy does not require finding a SPP which means that no realignment is required for every new sample, such that more measurements can be performed in shorter time. We believe that our strategy represents an interesting candidate for out-of-the-lab applications.

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Quantum-enhanced detection of atomic spins

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Sensitive detection of atomic spins is of relevance in a wide range of applications from the preparation of quantum states of matter [1] to the implementation of atomic sensors such as clocks and magnetometers. Equally attractive are those applications relying on unpolarized spins, for which statistical fluctuations in the spin orientation yield the signal [2–4]. Due to its fundamental nature spin-noise detection is challenging, often requiring sensitive and sophisticated tools such as magnetic resonance force microscopy [4] and magnetometers [5], for instance. Optical detection schemes based on Faraday rotation (FR), in which the spin noise is mapped onto the polarization of an off-resonant probe, are particularly attractive. Here we describe a versatile setup to optically prepare and detect alkali vapors using FR with both classical and non-classical light [6]. We perform spin noise spectroscopy (SNS) with Rb vapor [6] and study signal to noise ratio (SNR) as a function of probe power P and atomic density n. Our measurements show the interplay between enhanced sensitivity and disturbance with increasing power and density. While for small values of P and n SNR is linear in each (SNR $\propto nP$) at higher values light scattering and collisional effects disturb the system introducing deleterious effects, such as spin relaxation. We show that this relationship between sensitivity on the one hand and systematic effects on the other, can be improved by appropriate control of quantum statistics of the probe, i.e. squeezing.

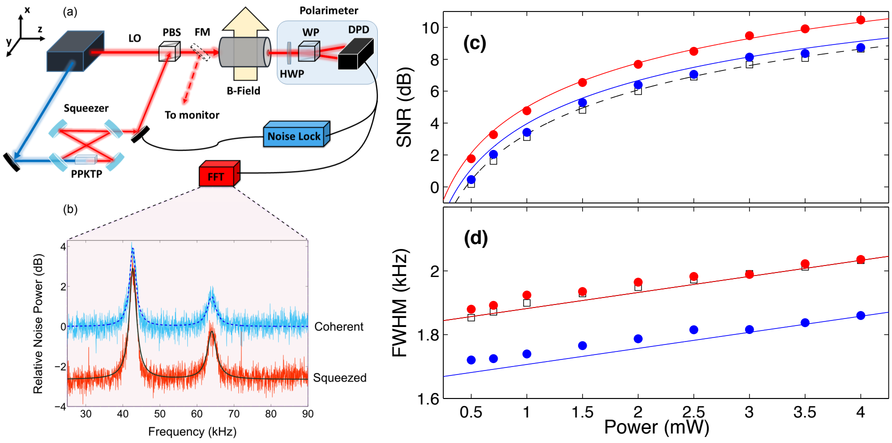

FIG. 1: (a) Experimental setup. LO - local oscillator, PBS - polarizing beam splitter, DPD - differential photo detector, FM - flip mirror, HWP - half wave-plate, WP - Wollaston prism, FFT - fast Fourier transform analyzer. (b) SNS Spectra. Averaged spin noise spectra acquired with coherent probe (cyan) and polarization squeezed probe (red) respectively. (c) SNR for ^{85}Rb versus optical power for coherent (empty black squares) and polarization squeezed (filled red circles) probing at $n = 0.9 \times 10^{13}\,\mathrm{cm}^{-3}$ and just for squeezed probe (filled blue circles) at lower density $n = 0.5 \times 10^{13}\,\mathrm{cm}^{-3}$. (d) Spin relaxation as measured by FWHM linewidth of the ^{85}Rb spin-noise spectrum vs probe power for the same conditions of (c). Dashed and continuous smooth curves in (b) show fits to the data and in (c) and (d) model predictions [6].

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Quantum Simulations & Processing - QSP

Boson Sampling in Continuous-Variable regime

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Building a universal quantum computer which exploits the peculiarity of quantum phenomena remains a challenging goal. As a result, proposals where subuniversal computations are considered have recently bloomed. One of those proposals, receiving a large attention, is Boson Sampling. In its implementation with single photons, n input photons are sent in m input ports of a linear optics network, and the probability distributions of the presence of photons in each output port of this network are sampled. These probability distributions have been shown to be proportional to the permanent of the submatrix which describes the linear network. Computing the permanent of a matrix is a problem believed to be hard classically [1]. These photonics networks stand as quantum platforms for the efficient solution of this problem, thereby providing a quantum advantage.

Here, we explored, from the theoretical point of view, the possibility of implementing the boson-sampling protocol presented in [2] by Ralph *et al.* in the context of a promising quantum optics experiment run in the continuous-variable (CV) regime [3]-[4], taking place in Laboratoire Kastler Brossel (LKB), and led by N. Treps and C. Fabre. To do so, we did a theoretical analysis necessary to adapt the CV-boson-sampling protocol to the experiment at LKB.

In conclusion, we provided an alternative description of the setup in [2], which explicits the use of independently squeezed states as a resource. Implementing this boson-sampling problem at LKB turned out not to be straightforward as the matrix directly implementable in this experiment does not possess yet the structure of the linear optics network needed to implement boson-sampling in CV. However, we started to consider other approaches, *e.g.* pump-shaping, in order to find the transfer matrix corresponding to the proposal of [2].

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Coined Quantum Walks with Restricted Percolation

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Quantum walks are of a significant interest in quantum information sciences. They are capable of universal quantum computing or performing specific quantum-walk algorithms and they may also serve as a simulator of other quantum systems. Further, quantum walks have potential to be practically used in future since they have already been experimentally realized in a variety of physical systems.

A discrete iterative evolution of coined quantum walks relies on a successful realization of two key ingredients - a coined unitary operation mixing internal degrees of freedom, followed by a conditional shift unitary operation spreading the quantum walker over positions of a certain graph. Unfortunately any realization suffers from imperfections. When some links of the graph are allowed to be broken or reopen again in an uncontrolled way we arrive at the concept of a quantum walk with percolation. Such a strong decoherence process is supposed to destroy all quantum coherences gradually and the quantum walk should become classical. However, it has been shown, that for quantum walks on finite graphs the process of dynamical percolation leads to a nontrivial asymptotic regime. In this regime, the state of the walk need not to be even stationary. There may be for example several-steps cycles via different quantum states [1].

In our contribution we first give a specific definition of the coined quantum walk. This definition is able to incorporate a variety of particular walks on arbitrary graphs. We also present a canonical way of how to define the evolution operator for a percolated walk. Our main interest is devoted to analysis of a scenario, when not all subsets of open edges are allowed in the percolation graph. For example, when only subsets with just one edge open in every step are possible. We call this scenario a quantum walk with a restricted percolation in contrast with the full percolation where all subsets are allowed.

For many types of restrictions, the restricted and the full percolation are equivalent in the sense that the resulting asymptotic evolutions coincide in both cases. Here, we present a sufficient condition which guarantees the same asymptotic dynamics for both coined quantum walks with either a restricted or with the full percolation. This condition applies to quantum walks defined on arbitrary graphs. We also provide some particular examples. This result can be of a great interest in experiments, where an implementation of all subsets of edges may be difficult or even impossible [2].

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Derandomizing quantum circuits with measurement based unitary designs

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Unitary transformations in a measurement based model are realized by making adaptive measurements on highly entangled multipartite quantum states. Such states are resources for universal quantum computation, but they can also give rise to ensembles of unitaries, a topic usually studied in the form of quantum circuits with randomly selected gates. Here we show that not only can these resources 'derandomize' circuit results by sampling the same kinds of ensembles quantum mechanically (analogously to a quantum random number generator), we find simple deterministic examples that give rise to new ensembles whose statistical moments exactly match those of the uniformly random distribution over all unitaries up to order t. Moreover, this foregoes adaptive correction (feed forward) entirely. In practice one often cannot distinguish such ensembles - known as t-designs - from the 'truly' random ensemble, and thus they find uses in many applications requiring this implied notion of pseudorandomness.

Randomness is an important resource in both classical and quantum information theory, with applications in cryptography, characterisation, and simulation. The fundamentally random nature of quantum measurement is well suited to many classical applications, and indeed industries now exist selling "truly" random number generators. In the quantum realm, random unitary transformations are often considered, in the form of random circuits, both theoretically (e.g. superdense coding[1], black hole information[2]) and in applications (e.g. estimating noise[3], modelling thermalisation[4], photonic implementations[5]). Uniform randomness, where one samples from the 'flat' Haar measure on a continuous group, is however very resource intensive. A natural definition of a less costly *pseudo*random ensemble is one whose statistical moments are equal to those of the Haar ensemble up to some finite order t – this is the defining property of a t-design. Designs have been studied in several contexts, both classical (with applications in *e.g.* experimental design, coding theory, and combinatorics) and quantum. Originally applied in the quantum community to states, here we will be concerned with processes[6, 7]. It turns out that for small systems, surprisingly few unitaries are required to 'simulate' the uniform ensemble in this way, and so they can be an attractive alternative in practice.

The existence of efficient unitary t-designs has been addressed in [8] where they showed that local random circuits are efficient t-designs. Nevertheless, to implement these for applications, in addition to an independent source of randomness, experimentally this requires realignment according to the sampled random classical string. For many set ups this can be prohibitively impractical.

Here we introduce the concept of a (deterministic) measurement based quantum unitary t-design. We show that a completely specified, graph state and a deterministic pattern of measurements can yield ensembles of unitary transformations on an arbitrary input that satisfy the t-design condition approximately and exactly. That is, our design is reached by the generation and measurement of entangled graph states only, with no feed forward or adaptivity, and randomness only coming from the quantum measurement. Our schemes can be realised with current experimental technology.

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Instantaneous Quantum Computing in Continuous Variables

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Even though building a universal quantum computer seems a daunting task, several schemes have been found for which weaker forms of quantum computers could still outperform classical ones. The most famous example of these sub-universal models of quantum computation is BosonSampling, which allows to efficiently sample the permanent of complex matrices – a problem thought to be hard for classical computers.

Another interesting sub-universal model is "Instantaneous Quantum computing", commonly referred to as IQP (for Instantaneous Quantum Polytime), defined for Discrete Variables (DV) in [1]. In the original formulation, an IQP circuit requires the following ingredients : the input states are Pauli-X eigenstates, each gate in the circuit is diagonal in the Pauli-Z basis and the output corresponds to a Pauli-X measurement. Since all the gates commute they can be performed in any order and possibly simultaneously, hence the name of IQP.

We study the translation of this class of circuits to the Continuous Variables (CV) formalism. From an experimental point of view, CV offer the possibility of deterministically preparing resource states, such as squeezed states or cluster states.

Our IQP mapping from DV to CV is based on the correspondence between the universal set of gates described e.g. in [2]. We define CV IQP circuits according to this procedure. They have the following structure : the input states are momentum-squeezed states, gates are diagonal with respect to the position quadrature and measurements are homodyne detections in the momentum quadrature.

In order to analyse the computational power of the CV IQP class we follow the lines of [1] by exploring the properties of post-selected CV IQP circuits. Post-selection in CV requires a careful analysis of the output distributions : by considering finite resolution homodyne detection we recover discrete sets of measurement outcomes. Furthermore, we show that finite resolution does not prevent the fault tolerance theorem of [3] from applying to CV Measurement Based Quantum Computing. These two properties together enable us to conclude that there is strong evidence that IQP in CV is hard to sample for a classical computer.

Since a demonstration of CV IQP seems within experimental reach, our proposal is a promising avenue to demonstrate quantum supremacy, i.e. a situation where a quantum device would outperform a classical one.

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Quantum Computing with Squeezing, Homodyne and Clicks

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Quantum information (QI) and quantum computation arise when the physical systems carrying information obey the rules of quantum mechanics. Classical information theory is mostly formulated in terms of encodings based on finite alphabets. The quantum counterpart is given by systems described in finite dimensional Hilbert spaces, namely discrete-variable (DV) systems. Many systems of interest are nevertheless associated with infinite-dimensional spaces, also called continuous-variable (CV) systems. A noteworthy example is provided by the electromagnetic (EM) field. The continuous variables are then provided by the quadratures of the field. Many notions studied in the DV case can still be given a meaning when going to CV. This is also true for Quantum Computation, for which a rigorous definition was provided by Lloyd and Braunstein [1]. This is given using the concept of universal set. Consider all unitary evolutions of m modes generated by hamiltonians which are polynomials in the quadrature operators. These can be approximated at will combining single mode gaussian operations, a single mode non-gaussian operation and a two mode entangling gate. Gaussian operations are generated polynomial hamiltonians up to second order in the quadratures. Non-gaussian evolutions are generated by higher order hamiltonians.

In the optical setting, gaussian operations correspond to propagation through linear optics, displacements and squeezing, which are fairly available in the lab. Entangling gates can be constructed as multimode gaussian operations, namely combining squeezers and a linear optical network. Non-gaussian gates are the most challenging. Some experimental proposals exist [3], but they require resources currently out of technological reach. Yet, non-gaussian have been shown to be necessary to see any quantum advantage [2].

An approach that recently attracted some attention is based on the observation that a unitary operator can be approximated by the beginning of its Taylor development [4]. This is a polynomial in the quadratures of the field, and even though it is not a unitary operator, it can approximate the evolution due to a polynomial hamiltonian if the evolution time is small enough.

We propose and analyze two new methods to implement polynomial gates using squeezed states and single photon sensitive detectors, without photon number resolution. They are inspired by the CV formulation of measurement-based paradigm for QC. In this paradigm, an entangled resource state is prepared in the beginning and computation is then driven by local (homodyne) measurements. Our first approach directly replaces the homodyne measurement with a single photon detector. The second method uses the single photon detector to herald the subtraction of a photon from a squeezed beam, generating a non-gaussian state ; the basic operation is then acted entangling the input mode and then performing on it a homodyne detection. We compare the methods to other existing proposals and discuss their advantages in the context of experiments based on optical frequency combs [5].

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Quantum information protocols in Continuous Variable

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Quantum information is the domain which aims at demonstrating and exploiting an advantage in the performances of quantum devices with respect to classical ones, for tasks related to information processing. Convincing results have been achieved in quantum metrology and quantum key distribution, while only proof-of-principles experiments have been performed so far in quantum computing. This difficulty is mainly due to the fact that producing and handling large entangled resource states, across which quantum coherence is maintained, is a challenging task.

Recently, an alternative approach for information encoding has become promising - the Continuous Variable (CV) approach, where information is encoded in observables characterized by a continuous spectrum [2]. This approach has allowed producing large entangled states of up to 10 000 modes [1].

I will summarize some contributions to the definition of quantum information protocols in CV. First I will address protocols for the generation and exploitation of CV resource states such as cluster states [3, 4] and surface code states, and discuss experimental implementations focussing on the set-up of N. Treps and C. Fabre at LKB [5, 6].

Later I will present new models of quantum computation in CV, which are less powerful than universal quantum computing, but which still display a quantum advantage over classical computing. Those models are less demanding in terms of experimental implementations, and hence could yield the first convincing observation of a quantum advantage for computation.

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

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

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

In addition our platform allows us to create and study the entanglement of many atoms. Relying on the Rydberg blockade, we can create an unique delocalized excitation over the entire ensemble of N atoms. The collective dynamics is then enhanced by a factor $\sqrt{N}$ that we recently measured up to N=15 [1].

We are now working on the creation of a long-lived $|W\rangle$ state [5] by bringing down the excitation to the hyperfine ground states $|F = 1, M = 1\rangle$ and $|F = 2, M = 2\rangle$. We plan to quantify the entanglement by applying global Raman rotations on the atoms [6].

We will present our results on the quantum simulation of a spin system and our latest progress towards the entanglement of a tens of atoms.

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Symmetry-protected topologically ordered states for universal quantum computation

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An intriguing connection between the resourcefulness in measurement-based quantum computation (MBQC) and certain phases of matter was discovered in Ref. [2], where the authors show that there exists a property of many-body states, namely symmetry-protected topological (SPT) order in 1D, that can be utilized for the protection of certain quantum gates in MBQC, even though 1D quantum states do not accommodate universal quantum computation. In Ref. [3, 4] the utility of SPT phases for quantum computation in 1D has also been demonstrated for other symmetry groups beyond the $Z_2 \times Z_2$ symmetry. Due to the potential advantage that SPTO may bring to MBQC, one question that arises naturally is whether we can find a novel universal resource state that exhibits nontrivial SPTO in two spatial dimensions or higher.

In Refs. [5, 6] the authors first discovered a consistent relation between the third group cohomology $\mathcal{H}^3(G, U(1))$ of a symmetry group G and SPTO in (2+1)D bosonic systems. Particularly, they prove that each nontrivial element of the third group cohomology corresponds to a distinct, nontrivial SPT phase. Specifically in Ref. [6], they discuss a fixed point wave function in its canonical form, showing that it exhibits nontrivial SPTO with respect to symmetry representations constructed from nontrivial elements in $\mathcal{H}^3(G, U(1))$.

In the paper [1] that I will present, we show that the canonical plaquette-like entanglement structure that displays nontrivial SPTO enables universal MBQC. Moreover, we prove that such entanglement structure defined on general 2D lattices is a universal resource. But does it also display nontrivial SPTO as in the square lattice ? To answer this, we explicitly extend the original symmetry construction to arbitrary lattices in two spatial dimensions. With the symmetry representation generalized, we can then show that these plaquette states and their generalizations on all 2D lattices indeed exhibit nontrivial SPTO, depending on the symmetry. We show that these states are universal resources for MBQC as long as their underlying graphs reside in the supercritical phase of percolation. This means that all (generalized) plaquette states on 2D regular or quasicrystallene lattices are both nontrivial SPT states and universal resources for MBQC.

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Universally Reconfigurable Linear Optics

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Linear optics underpins fundamental tests of quantum mechanics and quantum technologies. We demonstrate a single reprogrammable optical circuit that is sufficient to implement all possible linear optical protocols up to the size of that circuit [1]. Our six-mode universal system consists of a cascade of 15 Mach-Zehnder interferometers with 30 thermo-optic phase shifters integrated into a single photonic chip that is electrically and optically interfaced for arbitrary setting of all phase shifters, input of up to six photons, and their measurement with a 12-single-photon detector system.

The system is an ideal testbed for rapidly prototyping new linear optical quantum gates, and testing known protocols in experimentally realistic scenarios. We benchmarked the device by implementing 100 Haar random unitaries with an average fidelity of 0.999 ± 0.001 indicating high performance across the whole parameter space. We devise and implement a new scheme for heralded bell state generation, a key primitive in measurement-based linear optical quantum computing schemes. We perform a heralded CNOT gate for the first time in integrated optics and report the highest process fidelity achieved to date for a postselected CNOT gate. We propose and demonstrate techniques for efficiently characterising and verifying these gates.

The results presented required reconfiguration of this single device to implement ≈ 1000 experiments. The ability to arbitrarily reprogram linear optical devices promises to replace a multitude of existing and future prototype systems, pointing the way to applications across fundamental science and quantum technologies.

[1] J. Carolan *et al.*, "Universal linear optics", Science **349**, 711-716 (2015).

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