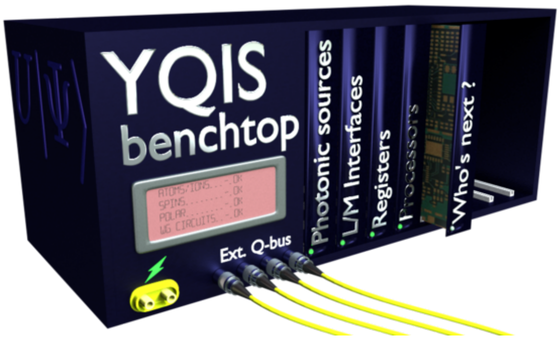
Book of Abstracts

INSTITUT d'OPTIQUE GRADUATE SCHOOL

BALZAN

PICQUE
Marie Curie Initial Training Network in Photonic Integrated Compound Quantum Encoding

GDR 3322 ⟨IQ|FA⟩ CNRS


YQIS
benchtop
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1 What is YQIS ?

1.1 An International Conference for Young Quantum Information Scientists

1.1.1 On YQIS' origins – The International Balzan Prize

Welcome to the First Edition of the International Conference for "Young Quantum Information Scientists" (YQIS),made by young researchers for young researchers (PhD students and post-doctroal fellows).

Initiated by **Alain ASPECT** (Institut d'Optique Graduate School, Palaiseau, France) and **Sébastien TANZILLI** (Université Nice Sophia Antipolis, France), see also Sec. 1.1.3, the first edition of YQIS will be held at the Institut d'Optique Graduate School in Palaiseau, France, and is made possible thanks to a fraction of the 2013 Balzan Prize awarded to Alain Aspect for his pioneering work in the field of quantum information and communication. Promoting pedagogical actions towards young research fellows is one of the major concerns of the International Balzan Prize Foundation.

1.1.2 On YQIS' scope

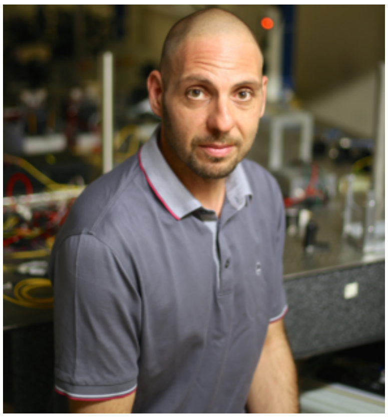
The fundamental properties of quantum physics are now considered as resources for the processing and the communication of information. Quantum Information Science (QIS) has established a new benchmark in communication and processing of information, thanks to protocols allowing augmented security in data exchange and increased processing capabilities. This young research field, lying at the interface of physics, computer science, mathematics and chemistry, has been driven by a strong international effort over the past fifteen years, with substantial rates of publications, patents, but also in terms of committed researchers. Quantum Information is now recognized as a full-fledged specialty, which motivated the formation of new teams. It is also a source of significant progress, both in terms of fundamental and applied technology, allowing for instance to coherently write and manipulate various quantum systems.

In this context, it is of utmost importance to permit young research fellows to benefit from their conference, in order to communicate on their research topic and exchange with others. YQIS thematics are broadband and cover both the theoretical and experiemtal sides, ranging from the very foundations of quantum information to applied quantum systems. In other words, all quantum information protocols are very welcome to be presented, whatever the quantum information carriers and the systems in which they are implemented. The thematics covered by YQIS are well summarized by the following artist view.

1.1.3 YQIS' fathers

Alain ASPECT (left) is Augustin Fresnel Professor at Institut d'Optique, Professor (part time) at École Polytechnique, and CNRS Distinguished Scientist (Directeur de recherche CNRS) emeritus at Laboratoire Charles Fabry. He is a member of the French Academy of Sciences and French Academy of Technologies. In 2005, he was awarded the Gold Medal of the Centre national de la recherche scientifique, where he is currently Research Director. The 2010 Wolf Prize in physics was awarded to Aspect, Anton Zeilinger and John Clauser. October 7, 2013, Aspect was awarded the Danish Niels Bohr International Gold Medal. In 2013 he was also awarded the Balzan Prize for Quantum Information Processing and Communication. The International Balzan Prize Foundation awarded Alain Aspect in 2013 "for his pioneering experiments which led to a striking confirmation of Quantum Mechanics as opposed to local hidden-variable theories. His work has opened the way to the experimental control of entangled quantum states, the essential element of Quantum Information Processing."

Sébastien TANZILLI (right) is a Research Director at CNRS, with the Laboratoire de Physique de la Matière Condensée (LPMC) at the Université Nice Sophia Antipolis (UNS). At LPMC, he leads the team "Quantum Information with Light & Matter" (QILM), which aims at exploiting integrated photonics and cold atomic ensembles as enabling technologies for quantum communication and information science. He was awarded the 2014 UNS outstanding research prize, one of the 2013 Grants from the Simone & Cino Del Duca (Institut de France) Research Foundation, the 2010 IXCORE Research Foundation prize, the 2009 CNRS Bronze Medal, and the 2008 Fabry-de Gramont Prize from the French Optical Society (SFO).

1.2 Scientific Committee of the YQIS' first edition

Members: Djeylan Aktas, Université Nice Sophia Antipolis (Nice, France),
Lucas Alber, Max Plack Institute for the Science of Light (Erlangen, Germany),
Martin Bouillard, Institut d'Optique Graduate School (Palaiseau, France),
Vanessa Chille, Max Plack Institute for the Science of Light (Erlangen, Germany),
Bruno Fedrici, Université Nice Sophia Antipolis (Nice, France),
Mauro Persechino, Institut d'Optique Graduate School (Palaiseau, France).

With the help of: Antoine Browaeys, Institut d'Optique Graduate School (Palaiseau, France),
Sébastien Tanzilli, Université Nice Sophia Antipolis (Nice, France).

2 YQIS' 1^{st} Edition – Scientific Information

2.1 Welcome !

YQIS' 1^{st} edition is mainly organized by the Laboratoire Charles Fabry de l'Institut d'Optique Graduate School (LCF-IOGS[1]). 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 young fellows, along 2 days, to exchange on the recent advances in the field. The colloquium will be outlined along 3 communication modes:

- 2 tutorial talks, given by Profs. Alain ASPECT (IOGS Palaiseau) and John RARITY (University of Bristol), having a clear pedagogical purpose, on the very foundations and most advanced applications of the field;
- 22 contributed/invited talks on the current hot topics within the strategic thematics (ARTs) identified by the GDR IQFA (see online the ARTs[2] for more details);
- and 2 poster session gathering 45 posters, again within the strategic thematics (ARTs) identified by the GDR IQFA.

In total this year, **YQIS' 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.

Martin BOUILLARD,
& **Djeylan AKTAS**,

On behalf of YQIS*' Scientific Committee.*

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

2.2 Program of the colloquium

Monday, November 16, 2015

TIME	EVENT
8:00 am - 8:45 am	Participants Registration - The participants will be provided with the program and a badge
8:45 am - 9:00 am	Opening - Welcome to the Participants (IOGS Theater) - Alain Aspect & Sébastien Tanzilli
9:00 am - 10:00 am	Hong-Ou-Mandel effect with Atoms (IOGS Theater) - Alain Aspect
10:00 am - 10:30 am	Coffee break (IOGS Atrium)
10:30 am - 10:55 am	On-chip heralded photon-number states generation (IOGS Theater) - Vergyris Panagiotis
10:55 am - 11:20 am	Entangled State Generation in Two-dimensional Nonlinear Lattices (IOGS Theater) - Stensson Katarina
11:20 am - 11:45 am	Temporal shaping of photons generated in parametric down-conversion with pulsed pump (IOGS Theater) - Averchenko Valentin
11:45 am - 12:10 pm	Preparation of Greenberger-Horne-Zeilinger and W States in Systems of Mutually Coupled Qubits (IOGS Theater) - Chakhmakhchyan Levon
12:10 pm - 12:35 pm	Genuine Multipartite Entanglement without Multipartite Correlations (IOGS Theater) - De Rosier Anna
12:35 pm - 2:00 pm	Lunch (Cafeteria Polytechnique)
2:00 pm - 2:25 pm	Encoding discrete quantum information in continuous variables: A modular variables approach (IOGS Theater) - Ketterer Andreas
2:25 pm - 2:50 pm	Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres (IOGS Theater) - Dréau Anaïs
2:50 pm - 3:15 pm	Relations between quantum walks and lifted random walks (IOGS Theater) - Apers Simon
3:15 pm - 3:40 pm	Detecting nonlocality in many-body systems with two-body correlators (IOGS Theater) - Baccari Flavio
3:40 pm - 4:05 pm	Hong-Ou-Mandel interferometry as a tool to probe decoherence (IOGS Theater) - Cabart Clément
4:05 pm - 4:30 pm	Coherent population trapping of a single nuclear spin under ambient conditions (IOGS Theater) - Jamonneau Pierre
4:30 pm - 5:00 pm	Coffee break (IOGS Atrium)
5:00 pm - 6:30 pm	Poster Session 1 - Poster Session 1 in the Atrium

Tuesday, November 17, 2015

TIME	EVENT
9:00 am - 10:00 am	Hong-Ou-Mandel effect with Photons (IOGS Theater) - John G. Raity
10:00 am - 10:30 am	Coffee break (IOGS Atrium)
10:30 am - 10:55 am	Instantaneous Quantum Computing in Continuous Variables (IOGS Theater) - Douce Tom
10:55 am - 11:20 am	Quantum simulation of spin systems using 2D arrays of single Rydberg atoms (IOGS Theater) - De Léseleuc Sylvain
11:20 am - 11:45 am	Quantum computing with squeezing, homodyne and clicks (IOGS Theater) - Arzani Francesco
11:45 am - 12:10 pm	Algorithmic Cooling in Liquid State NMR (IOGS Theater) - Elias Yuval
12:10 pm - 12:35 pm	Optimal randomness generation from optical Bell experiments (IOGS Theater) - Mattar Alejandro
12:35 pm - 2:00 pm	Lunch (Cafeteria Polytechnique)
2:00 pm - 2:25 pm	Entanglement-based high-accuracy chromatic dispersion measurements (IOGS Theater) - Kaiser Florian
2:25 pm - 2:50 pm	Bounds on entanglement distillation and secret key agreement capacities for quantum broadcast channels (IOGS Theater) - Seshadreesan Kaushik
2:50 pm - 3:15 pm	Broadcasting of Quantum Correlations: Possibilities & Impossibilities (IOGS Theater) - Sourav Chatterjee
3:15 pm - 3:40 pm	Coherent Spin Control at the quantum level in an ensemble based optical memory (IOGS Theater) - Laplane Cyril
3:40 pm - 4:05 pm	Non-classical correlations between a C-band telecom photon and a spin wave in an atomic ensemble quantum memory (IOGS Theater) - Maring Nicolas
4:05 pm - 4:30 pm	A Nanofiber-based Memory for Light (IOGS Theater) - Gouraud Baptiste
4:30 pm - 5:00 pm	Coffee break (IOGS Atrium)
5:00 pm - 6:30 pm	Poster Session 2 - Poster Session 2 in the Atrium

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 (head: Laurent Sanchez-Palencia & Christoph Westbrook),
- Quantum Optics (head: 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 1^{st} YQIS *Edition.*

3 YQIS' 1^{st} Edition – Practical Information

3.1 Registration & Internet Connection

The participants' registration will be made available from Monday the 16^{th} 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 19^{th} 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.

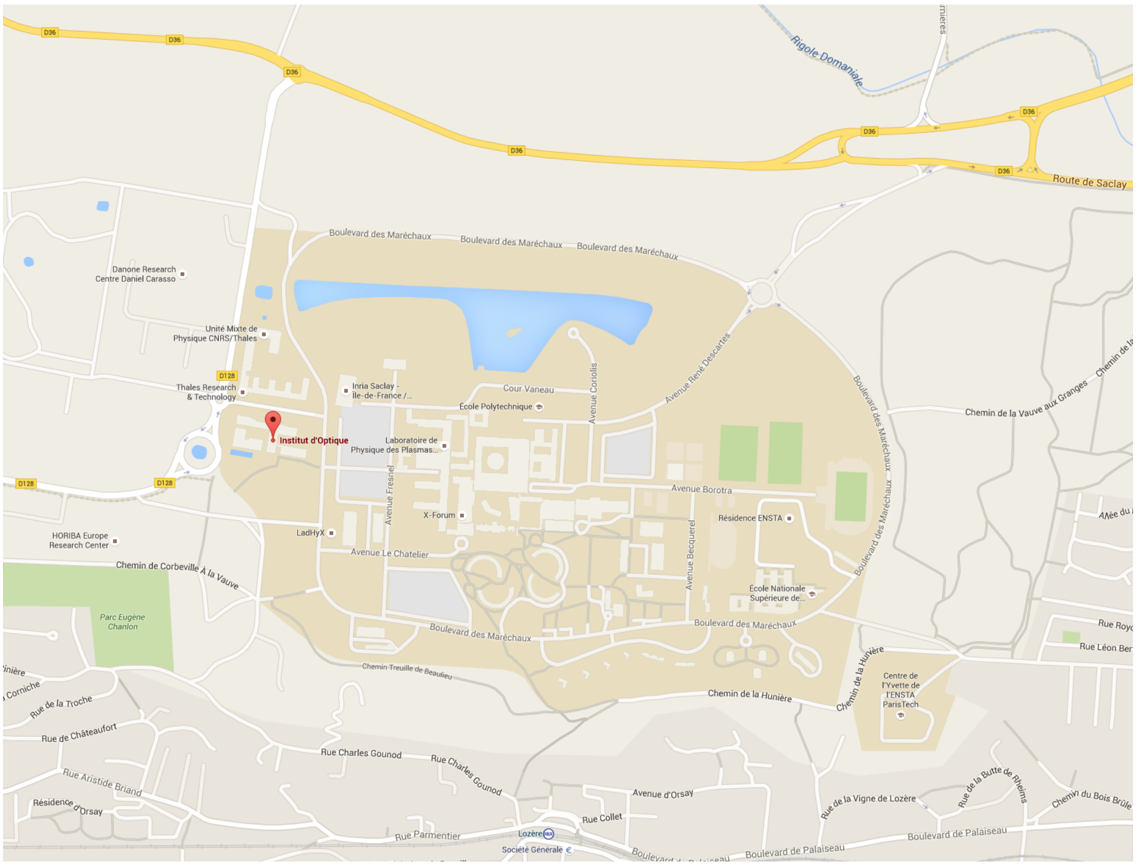
3.4 Venue

YQIS's 1^{st} edition 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 newt to the amphitheater, in the same building. The participants will be driven on site.

3.5 Localization map

Access to the 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.



Localization map of the IOGS and surrounding area.

- *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 YQIS's 1st edition, please refer to its webpage at: How to reach YQIS's 1st edition[3].

3.6 Organization & financial supports

YQIS*'s 1st edition is organized by:*	the IOGS and the GDR IQFA,
at, and with the help of:	the Laboratoire Charles Fabry (LCF-IOGS, CNRS, UPSUD),
and with the logistical & financial supports of:	the International Balzan Prize Foundation, the Institut d'Optique Graduate School (IOGS), the GDR IQFA, the FP7 International Training Network project PICQUE *("photonic integrated compound quantum encoding")*,
vspace0.2cm	*that are warmly acknowledged.*

[3] http://yqis15.sciencesconf.org/resource/acces

3.7 Local organization committee for this colloquium

Members: Martin Bouillard (LCF-IOGS, UMR 8501, Palaiseau),
Mauro Persechino (LCF-IOGS, UMR 8501, Palaiseau),
Antoine Browaeys (LCF-IOGS, UMR 8501, Palaiseau),
Nathalie François (LCF-IOGS, UMR 8501, Palaiseau), for admin support,

with the remote help of: Sébastien Tanzilli & Bernard Gay-Para (LPMC, UMR 7336, Nice).

4 Abstracts of the contributions

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

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Tutorials

Hong-Ou-Mandel effect with Atoms

Alain Aspect*
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Hong-Ou-Mandel effect with Photons

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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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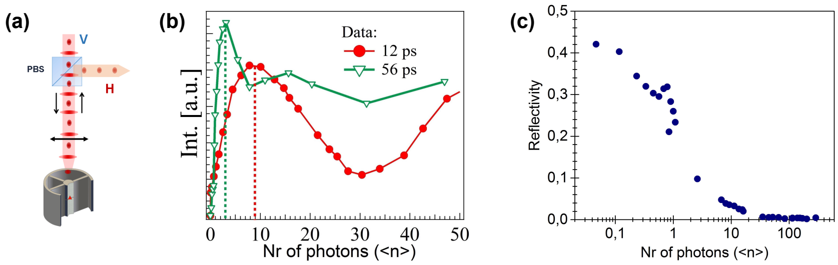
[2]*Université Grenoble Alpes, 38000 Grenoble, France*
[3]*Université Paris Diderot - Paris 7, 75205 Paris, France*
[4]*Physics Department, Ecole Polytechnique, 91128 Palaiseau, France*

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 population trapping of a single nuclear spin under ambient conditions

P. Jamonneau[1], G. Hétet[1,2], A. Dréau[1], J.-F. Roch[1], and V. Jacques[1,3]*
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[2]*Laboratoire Pierre Aigrain, CNRS, Université Pierre et Marie Curie,*
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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].

[1] A.Aspect, et al, Phys. Rev. Lett. **69** 1360 (1992).
[2] J. Vanier, Appl. Phys. B **81**, 421 (2005).
[3] X.Xu, et al, Nat. Phys. **4**, 692 (2008).
[4] E. Togan, et al, Nature **478**, 497 (2011).
[5] M. A. Sillanpää, Phys. Rev. Lett. **103**, 193601 (2009).
[6] P. Jamonneau, et al, submitted
[7] Y. Kubo, et al, Phys. Rev. Lett. **107**, 220501 (2011).

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

T. R. Tan,* J. P. Gaebler, Y. Lin, Y. Wan,† R. Bowler‡, D. Leibfried, and D. J. Wineland

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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.

Supported by Office of the Director of National Intelligence (ODNI) Intelligence Advanced Research Projects Activity (IARPA), ONR, and the NIST Quantum Information Program.

[1] T. R. Tan *et al.*, arXiv:1508.03392 (2015).

[2] M. Wallquist, L. Hammerer, P. Rabl, M. Lukin, and P. Zoller, Phys. Scr. **T137**, 014001 (2009).

[3] A. Sørensen and K. Mølmer, Phys. Rev. Lett. **82**, 1971 (1999).

[4] G. J. Milburn, S. Schneider, and D. F. V. James, Fortschr. Phys. **48**, 801 (2000).

[5] E. Solano, R. L. de Matos Filho, and N. Zagury, Phys. Rev. A **59**, R2539 (2008).

[6] J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, Phys. Rev. Lett. **23**, 880 (1969).

[7] M. A. Nielson and I. L. Chuang, (Cambridge Univ. Press, Cambridge, 2000).

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Entanglement & Nonclassical States - ENS

A general dichotomization procedure to provide qudits entanglement criteria

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[3] *Laboratoire Matériaux et Phénomènes Quantiques, Université Denis Diderot, CNRS UMR 7162, 75013, Paris, France*

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.

[1] I. Saideh, et al. , " A general dichotomization procedure to provide qudits entanglement criteria", arXiv :1508.01684 [quant-ph].

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A tunable narrowband photon-pair source for quantum information processing

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Single photons and photon pairs are an important element in quantum information processing protocols. We will review our compact source of photon pairs and squeezed light based on efficient spontaneous parametric down conversion (SPDC) in a triply resonant whispering-gallery resonator (WGR) made of lithium niobate [1–4]. Single-mode operation of this source has been demonstrated in [5]. The central wavelength of the emitted light can be tuned over hundreds of nanometer. This allows for precise and accurate spectroscopy with heralded single photons of tunable bandwidth. We demonstrated tuning to the D1 lines of rubidium (795 nm) and cesium (895 nm). The corresponding idler photons are emitted at 1317 nm and 1609 nm for cesium and rubidium respectively [6].

Providing this flexibility in connecting various alkali atoms with telecom wavelengths, this system opens up novel possibilities to realize proposed quantum repeater schemes. The feasibility of practical quantum repeater schemes will benefit from the development of better sources for photon pairs. We are currently working on implementing a scheme of SPDC with counter-propagating beams in one WGR in order to investigate the interference of two heralded photons.

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Correlation-based entanglement criterion in bipartite multiboson systems

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We describe a criterion for the detection of entanglement between two multi-boson systems. The criterion is based on calculating correlations of Gell-Mann matrices with a fixed boson number on each subsystem. This applies naturally to systems such as two entangled spinor Bose-Einstein condensates. We apply our criterion to several experimentally motivated examples, such as an $S^z S^z$ entangled BECs, ac Stark shift induced two-mode squeezed BECs, and photons under parametric down conversion. We find that entanglement can be detected for all parameter regions for the most general criterion. Alternative criteria based on a similar formalism are also discussed together with their merits.

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Efficient generation of photon-pairs using a silicon microring resonator

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Silicon-on-Insulator (SOI) technology has already proven to be an efficient solution to implement many integrated optical devices [1]. In the quantum field, and in particular for Quantum Key Distribution (QKD) applications, many studies have also shown that SOI waveguides are suitable $\chi^{(3)}$ nonlinear sources of energy-time entangled photon pairs [2]. However, the waveguide technology demonstrated so far requires millimetre lengths to produce significant photon pairs rates. Silicon ring resonators, thanks to cavity enhancement effect in term of power and optical length, offer an attainable solution to the scalability and dense integration problem [3].

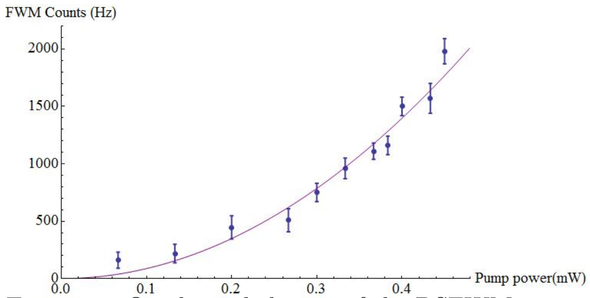

FIGURE 1: Quadratic behavior of the DSFWM versus the pump power.

The aim of this work is to demonstrate energy-time entanglement of photon pairs generated through Degenerate Spontaneous Four Wave Mixing (DSFWM) process in continuous pump regime with a Si on Insulator (SOI) structure, which enjoys a high index difference between the core of Si and Silica cladding. The wavelength of the pump laser (1539 nm) is adjusted at a resonance of the frequency comb induced by the ring cavity, to obtain signal and idler photons within the telecom C-band. The free spectral range is about 1.8 nm, and the resonance quality factor is around 30000. For a given pump power, the photon pairs rate produced by DSFWM is proportional to the ratio $\frac{Q^3 P^2}{R^2}$, which is shown in Fig. 1. From this curve, we can infer a large internal generation rate and a high spectral brightness of 2 Mpairs/S and $3 \cdot 10^4\,(\mathrm{nm} \cdot \mathrm{mW} \cdot \mathrm{s})^{-1}$, respectively, which are among the best results reported to date with similar systems [4].

Furthermore, a crucial step to verify entanglement is to check that signal and idler photons are emitted in pairs thanks to a coincidence experiment. We obtained a very clear coincidence peak with Full Width at Half Maximum (FWHM) of 200 ps, which is consistent with timing jitter of single-photon detectors (SPDs). We measured a coincidence to accidental ratio (CAR) of 20, making this source a promising candidate for being at the heart of QKD systems. Peculiar attention has to be carried out to improve the light collection at the output of the chip to increase the CAR and to foresee low noise wavelength division multiplexed quantum system based on Si microring cavity.

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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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Enhancing quantum measurement of optical phase with squeezed states

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By measuring globally two conjugated squeezed states, we enhance the precision on the measurement of correlations between the quadratures compared to individual measurements. These correlations are related to the optical phase of the squeezed states. We propose a measurement scheme which enhances the measurement of theses correlations up to a factor $\sqrt{2}$.

Our measurement scheme is build on two main ideas which seems foundamental. The first of them is global measurement. A. Peres and W. K. Wootters conjectured in 1991 that considering a system composed of two $\frac{1}{2}$-spins globally can gives us a better knowledge of their orientation in space than measuring them individually [1]. This conjecture was proven for finite quantum systems in 1995 by S. Massar and S. Popescu [2]. We implement this idea of global measurement by using a 50/50 beamsplitter to entangle our two input.

The second idea was introduced by N. Gisin and S. Popescu in 1999 [3]. They showed that measuring globally a system composed of two antiparallel $\frac{1}{2}$-spins gives us more information than two parallel one's. This purely quantum effect exist because of the anti-unitary nature of the spin-flip operation. We use it in our measurement scheme by starting with two conjugated squeezed states.

In order to enhance the optical phase measurement, we use phase-squeezed states which are the non-classical quantum states which suits the best for our goal. Our global measurement scheme is decomposed in three steps and has already shown his advantages for the measurement of two coherent states [4]. First, we consider two vacuum squeezed states which are conjugated one to the other. Then, we input these states in a 50/50 beamsplitter to entangle the two squeezed states. Finally, we make homodyne detections on the correlated quadratures of the two different output modes. We found the explicit relation between the correlations of conjugated quadratures of different output modes and the initial optical phase of the squeezed states. We have compared the relative errors of a global measurement versus individual measurements where we measure the quadratures directly on the squeezed states. We found an asymptotical enhance of the measurement of the correlations by a factor $\sqrt{2}$. Mathematically, it can be written as:

$$\lim_{r\to\infty} \frac{\delta_{xp}}{\delta_{x'p'}} = \sqrt{2},$$

where r is the *squeezing parameter*, δ_{xp} the relative error accorded to individual measurements and $\delta_{x'p'}$ the relative error accorded to global measurement. Actually, we can interpret this result in the following way: for any phase angle $\phi \in]0, \frac{\pi}{4}[$, there exist always a squeezing parameter r^* such that global and individual correlation measurements on squeezed states have the same relative error. For $r > r^*$, the global measurement is better than the individual one.

This result is in agreement with theses of [4]. However, there is still no proof of optimality of this kind of measure. We assume in our work perfectly conjugated states. The case with a certain error on the conjugation is a possible perspective for further work.

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Entangled State Generation in Two-dimensional Nonlinear Lattices

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Since the success of the periodic poling method to achieve quasi-phase matching (QPM), the process of parametric down-conversion has established itself as the main source of the non-classical photon states needed for practical quantum technologies as well as for fundamental tests of quantum mechanics. The realization of 2D QPM through periodic poling in two dimensions results in greater complexity [1], and allows preparation of states that would normally need several down-converters and optical elements, making it a tempting option for compact state preparation devices. Examples of such states include the 2-photon NOON state and, in focus here, the two photon state distributed over three spatial modes, originally described in the 1991 paper by Zou, Wang and Mandel [2], where the alignment of the idlers from two separate down-converters induce coherence between their corresponding signals. The coherence is a result of the indistinguishability of the idlers, a feature that is reproducible by a hexagonally poled 2D QPM crystal alone. In fact, the processes generating two signal modes coupled through their indistinguishable idlers, are enhanced, showing an extra factor $\sqrt{2}$ in the gain coefficient. The idler, shared between the two signal modes, can be used for heralding a single photon path-entangled state, discussed for the use in quantum key distribution [3] and quantum teleportation [4].

The down-conversion process in a QPM crystal is characterized by the phase-matching conditions

$$\omega_p = \omega_s + \omega_i \qquad \mathbf{k_p} = \mathbf{k_s} + \mathbf{k_i} + \mathbf{G_m}$$

Where $\omega_{p,s,i}$ and $\mathbf{k_{p,s,i}}$ represent the pump, signal and idler frequencies and wave vectors, and the phase mismatch is accounted for by the 1^{st} order reciprocal lattice vectors $\mathbf{G_m}$, $\mathbf{m} = 1, 2$, as illustrated in fig. 1. For this work we use hexagonally poled, Mg-doped, stoichiometric $LiTaO_3$ (hexSLT, Oxide corp.). Samples with poling periods $\Lambda = 8.3$ and 8.5 μm, pumped by 532 nm frequency doubled NdYAG, generate signals and idlers around 800 and 1550 nm respectively, chosen to allow optimized detection of the heralding photon and fiber-optic transmission of its twin.

Characterization of the down-conversion process using these samples show good agreement with theory. Ongoing experiments aim to investigate the heralded single photon path-entangled state, as well as higher order states involving 4 photons. 2D QPM appears especially promising in the quest for compact solutions for photonic state generation. Ongoing and future work aim to explore this potential and facilitate its practical implementation.

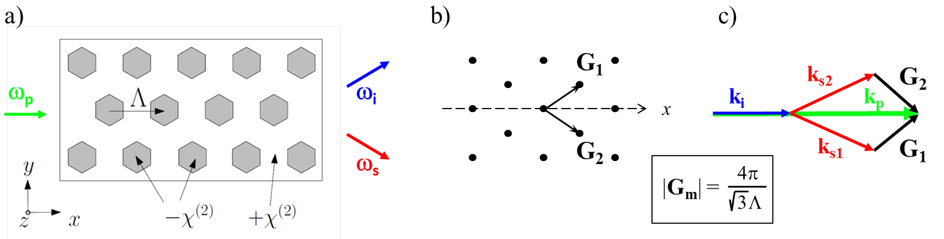

FIGURE 1: Hexagonally poled SLT. Illustration of a) real and b) reciprocal space. c) Shared idler phase-matching configuration using RLVs $\mathbf{G_1}$ and $\mathbf{G_2}$.

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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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Finite-temperature reservoir engineering and entanglement dynamics

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We propose experimental methods to engineer reservoirs at arbitrary temperature which are feasible with current technology. Our results generalize to mixed states the possibility of quantum state engineering through controlled decoherence [1, 2]. Finite-temperature engineered reservoirs can lead to the experimental observation of thermal entanglement–the appearance and increase of entanglement with temperature [3]–to the study of the dependence of finite-time disentanglement and revival with temperature, quantum thermodynamical effects, and others, enlarging the comprehension of temperature dependent entanglement properties. Our proposal is discussed in detail in two model systems, consisting of different modes of a single photon and a trapped-ion system.

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Genuine Multipartite Entanglement without Multipartite Correlations

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Nonclassical correlations between measurement results make entanglement the essence of quantum physics and the main resource for quantum information applications. Surprisingly, there are multiparticle states which do not exhibit multipartite correlations at all but still are genuinely multipartite entangled. We introduce a general construction principle for such states, implement them in a multiphoton experiment and analyze their properties in detail. Remarkably, even without multipartite correlations, these states do violate Bell inequalities showing that there is no classical, i.e., local realistic model describing their properties.

Homodyne iterative tailoring of mesoscopic states of light

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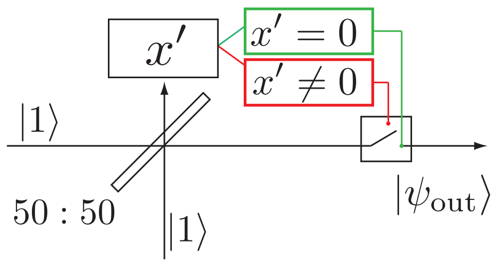
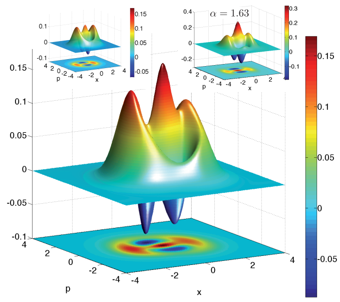
Tailoring arbitrary states of light is a main challenge in quantum optics, as photons are particles that do not interact with each others. In order to circumvent this issue, current techniques take benefit of entangled states of light and perform a measurement in one of the subsystems. This way, superposition of two [1] or three [2] photons have been produced and characterized.

A main drawback of all the currently used techniques is the fact that they rely on the simultaneous detection of an increasing number of photons for an increasing size of the state, leading to very low success probability for a photon number greater or equal than four. We propose here a new technique, based on the coherent adjunction of single photons Fock states in order to grow iteratively the size of the state, *i.e.* to increase iteratively the mean photon number of the state [3]. The elementary protocol simply consists in mixing an input state $|\psi_{\text{in}}\rangle$ with a single photon Fock state on a partially reflective beamsplitter and by realizing a homodyne conditioning in one of the two output ports. The other output port will then be projected on a state $|\psi_{\text{out}}\rangle$, which contains a greater mean photon number than $|\psi_{\text{in}}\rangle$. We also show that if this protocol is iterated n times, if the beamsplitters reflectivity and the homodyne conditionings are well chosen, arbitrary superposition of n photons can be produced. The great advantage of this new protocol is that it enables the use of quantum memories between each iteration, allowing for a very high success probability of the setup.

We experimentally demonstrate the validity of this protocol by producing coherent state superposition : the so-called "Schrödinger Cat States" (SCS). The protocol is show in figure (a), and consists in this case in mixing two single photons on a symmetrical beamsplitter and performing a homodyne conditioning at 0 in one output port. The Wigner function, shown in figure (b) of the created state is reconstructed and has 61% fidelity with an ideal SCS of amplitude $\alpha = 1.63$ squeezed by $s = 1.52$ along the quadrature x [4].



(a)



(b)

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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].

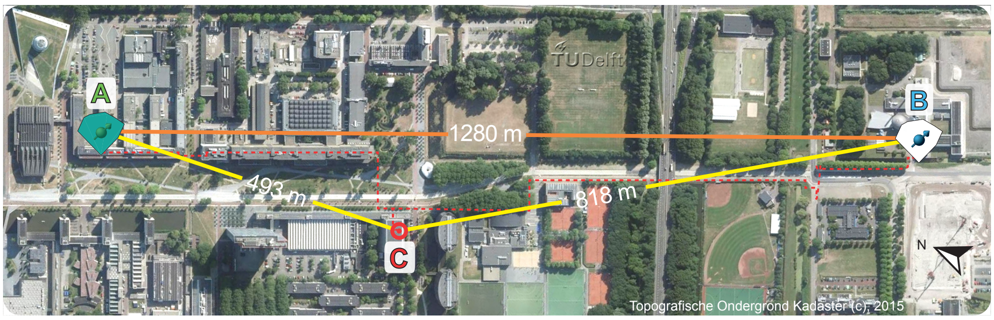

FIGURE 1. Aerial photograph of the campus of Delft University of Technology where entanglement was generated between two electron spins in diamond located at positions A and B. The location C serves as an intermediate station necessary for the remote entanglement protocol. The red dotted line marks the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

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Observable measure of quantum coherence

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Quantum coherence is a key resource for quantum technology, with applications in quantum optics, information processing, metrology and cryptography. Yet, there is no universally efficient method for quantifying coherence either in theoretical or in experimental practice. I introduce a framework for measuring quantum coherence in finite dimensional systems [1]. I define a theoretical measure which satisfies the reliability criteria established in the context of quantum resource theories. Then, I present an experimental scheme implementable with current technology which evaluates the quantum coherence of an unknown state of a d-dimensional system by performing two programmable measurements on an ancillary qubit, in place of the $O(d^2)$ direct measurements required by full state reconstruction. Also, I propose an experimental strategy to witness the presence of entanglement in multipartite systems by evaluating coherence. The results yield a benchmark for monitoring quantum effects in complex systems, e.g. certifying non-classicality in quantum communication and simulation protocols and probing the quantum behaviour of biological complexes.

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On-chip heralded photon-number states generation

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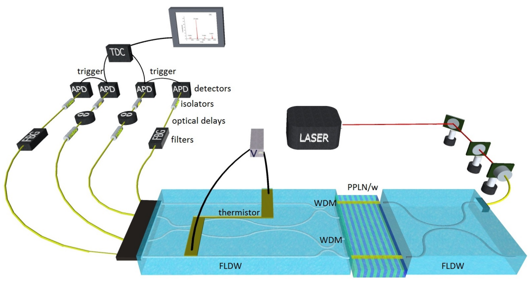
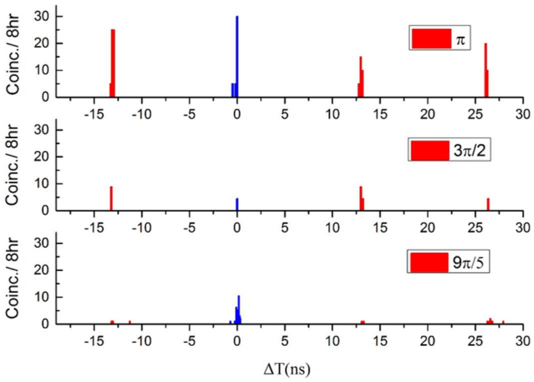
Recent progress in the field of quantum information processing has highlighted the prospects of using integrated optical devices for quantum applications. Integrated quantum photonics offers several advantages compared to free-space setups. Not only the miniaturization, which dramatically reduces the 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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Optical Hybrid Quantum Information processing

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The wave-particle duality of light has led to two traditionally separated encodings for optical quantum information processing. The discrete-variable (DV) approach involves single photons and qubits living in a finite dimensional Hilbert space, for example absence or presence of a single photon : $c_0|0\rangle + c_1|1\rangle$.

The continuous-variable alternative (CV) encodes information into the quadrature components of the light field in an infinite-dimensional Hilbert space. Qubits can be implemented for instance as coherent state superpositions (CSS), $|cat\pm\rangle = |\alpha\rangle \pm |-\alpha\rangle$ where $|\alpha\rangle$ is a coherent state with a mean photon number $|\alpha|^2$, also called Schrödinger cat states as a reminder of the famous thought experiment. Those states are critical resources in the emerging field of optical hybrid quantum information [1]. A well-known and seminal protocol to generate odd optical cat states of size $|\alpha|^2 \sim 1$ is based on photon subtraction operated on squeezed vacuum state. To reach higher mean photon values, experiments have focused on multiple subtractions or cascaded conditionings, and, so far, the only possibilities for generation intrisically resulted in a low generation rate at the Hz level. In this talk, I will review recent experiments at LKB, aiming at generating large-amplitude even squeezed CSS with a size $|\alpha|^2 = 3$ and a fidelity of 67% recently passed to 77%. This scheme relies on a two-mode squeezed state, linear mixing and a n-photon detection. The generated state exhibits the highest amplitude and fidelity reported to date for free-propagating CSS, and importantly a preparation rate about 200 Hz is achieved, as we report in [2].

Finally, we demonstrate hybrid entanglement between optical qubits of CV and DV types, located at distant places and heralded by single photon detection in an indistinguishable process [3]. Beyond its fundamental significance for the exploration of entanglement and its possible instantiations, this novel entanglement of light holds promise for implementations of heterogeneous networks, where discrete- and continuous-variable operations and techniques can be efficiently combined. Indeed, as both encodings have their advantages and drawbacks, transferring information between them is a requirement which can be provided by teleportation using hybrid entanglement between particle-like qubits and wave-like qubits, i.e. state of the form $|+\rangle|\alpha\rangle + |-\rangle|-\alpha\rangle$, where $|\pm\rangle$ refers to the two-level qubit system. In contrast to proposals based on dispersive light-matter interactions or Kerr non-linearities, by using two OPOs pumped below threshold [4][5], we devise an optical circuit where the generation of such hybrid entangled state is heralded at a distance by the detection of a single photon. The losses on the conditioning channel affects the count rate but not the fidelity of the generated state and are equivalent to 75 km of fiber at telecom wavelength, confirming the reliabitilty of our method to establish entanglement on long distances.

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Practical Measurement Device Independent Entanglement Witness

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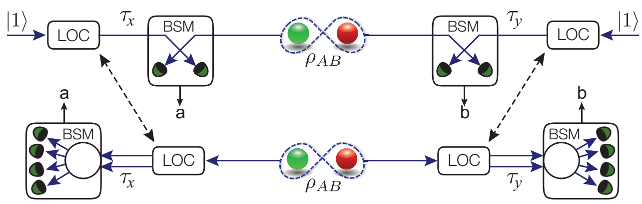
Entanglement is one of the quintessential characteristics of quantum physics and is a valuable resource in emerging quantum technologies. A reliable verification and characterization of entanglement is therefore critical for many applications and protocols. Various methods have been proposed to demonstrate 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 $\mathrm{Tr}[\rho W] < 0$, 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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Preparation of Greenberger-Horne-Zeilinger and W States in Systems of Mutually Coupled Qubits

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We consider systems of two and three mutually coupled qubits, interacting with external laser fields. We show that these systems allow one to create maximally entangled Bell states, as well as three-qubit Greenberger-Horne-Zeilinger (GHZ) and W states, which are an essential building block for quantum communication and quantum information processing. The mutual interqubit interaction is chosen here of a Heisenberg-type exchange character, that arises in various systems, including coupled semiconductor quantum dots (as well as in the exciton/biexciton system of a single semiconductor quantum dot, that acts as a two-qubit register), superconducting phase and charge qubits, atoms (ions) trapped in a cavity (ion trap) within the dispersive limit, highly excited Rydberg atoms, etc [1]. We show that within the above model all four Bell states, GHZ and W states can be generated from a non-entangled ground state by means of adiabatic (stimulated Raman adiabatic passage (STIRAP), fractional STIRAP, rapid adiabatic passage) and pulse area techniques [2], each of which have their own advantages [3]. Furthermore, our method allows one to manipulate the amount of the entanglement in a continuous way, by fixing, e.g., the area of the incident laser pulse. Finally, by the analysis of the eigenstate structure of the initial bare system of intercoupled qubits, we also discuss the possibility of generalizing the proposed schemes for the preparation of N-qubit GHZ and W states with $N > 3$.

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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 Uncertainty in the Beam Width of Spatial Optical Modes

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Quantum fluctuations of light affect the spatial characteristics of a light beam, such as position and width, and set limits to applications such as imaging and beam focusing. In this work, we investigate how quantum noise gives rise to uncertainty in the measurement of the width of an optical beam. Our starting point is the definition of a quantum operator representing the beam width. We study its variance in detail for single-mode states as well as for the more general case of multimode bright states. One of our findings is that the noise in the beam width can be attributed to the amplitude noise of a single spatial mode uniquely specified by the spatial profile of the beam itself.

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Temporal shaping of photons generated in parametric down-conversion with pulsed pump

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Heralding a single photon from a photon pair generated by spontaneous parametric down-conversion is the most reliable way to generate pure, single mode photons up to date [1]. Next step is to tailor photon properties, such as temporal and spatial profiles and polarization pattern. The motivation is the following - tailored photons are superior in a number of optical tasks, where light intensity is restricted to a single quanta level. Amongst them we recall efficient excitation of a single quantum emitter (single atom, molecule, quantum dot, etc.), quantum information processing with single photons and quantum emitters.

In this work we study temporal shaping of heralded photons by tailoring pump pulses, which drive the parametric process in the resonator-assisted configuration. Under these conditions the optical resonator defines the mode of the generated photons and makes them suitable for several quantum optics applications. In turn, pump modulation provides an additional control over temporal properties of heralded photons.

The adopted theoretical model is a triply-resonant optical parametric oscillator operating far below the oscillation threshold. Such model reproduces the main features of the experiment on spontaneous parametric down-conversion in a monolithic nonlinear whispering gallery mode resonator (WGMR). Recently, the generation of narrowband and wavelength tunable heralded photons has been demonstrated with this setup [2]. Here, we calculate the temporal distribution of the generated signal photons excited by different temporally shaped pump pulses and find good agreement with the corresponding measurements.

Developed model will provide a theoretical basis to study the dynamics of quantum light generation from a WGMR with temporally modulated pump pulses. In particular, it describes the generation of temporally shaped heralded photons. Also, our results furnish a contribution to the quantum theory of the cavity-assisted non-stationary parametric fluorescence.

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Towards Raman-free Entangled Photon Pairs Generation in Liquid-filled Hollow-core Photonic Crystal Fibers

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The generation of entangled photon pairs in fibers is the first step towards future quantum communication networks. We present here a fibered source based on four-wave mixing into its liquid-core to generate time-correlated photon pairs, which can be entangled through a Sagnac loop structure.

The nonlinear medium is a liquid filling the hollow core of a photonic crystal fiber. Time-correlated photon pairs are generated in spontaneous regime. The four-wave mixing occuring in our nonlinear medium allows the annihilation of two pump photons in order to generate simultaneously signal and idler photons. The process fulfils the energy and momentum conservation conditions, the latter one being satisfied when the pump wavelength is close to the fiber's zero-dispersion wavelength.

In silica-core fibers [1] uncorrelated noise photons are generated due to Raman scattering. We present here a solution proposed by our group [2] that consists in keeping the fibered structure and using a liquid nonlinear medium. Compared to the broadband Raman spectrum of silica, liquids have the very important advantage to provide narrow Raman lines. Guidance of light along the fiber is provided by a photonic crystal structuration in its cladding. Its filling with a liquid with a refractive index of 1,36 (such as acetone-d6) generates a transmission band in the 700-1000nm range, allowing to reject the major Raman lines.

Our pump is a pulsed Ti :Sapphire laser injected into our fiber, while the output is injected in a home-made double-grating spectrometer with two arms, for signal and idler detection. Pump, signal and idler wavelengths are first determined from the calculated probability density of a parametric photon pair generation [3], and then reajusted experimentally. The knowledge of nearest Raman lines positions from previous measurements allows us to position signal and idler wavelengths between them, which leads to a Raman noise extinction of 30dB compared to silica fibers. The double-grating configuration separates signal and idler wavelengths from the pump, with an extinction of 130dB [3]. The signal and idler photon detection is operated by fibered silicon single-photon detectors linked to a time-corelation system.

We evaluate our source quality by measuring the *Coincidence-to-accidental Ratio* (CAR), which corresponds to a signal-to-noise ratio. Recent measurements give a CAR of 60 with a commercial fiber that is not optimized to be filled. These encouraging results lead us to the next step for photon pairs entanglement : integration of the fiber into a Sagnac loop configuration. I will present in details our experiment and the characterization of the generated correlated pairs along with the first results about the Sagnac loop implementation for polarization entanglement generation.

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Towards quantum nonlinearities in an intracavity Rydberg medium

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The realization of a strong and deterministic photon-photon interaction is a challenging task, but could enable the implementation of a two-photon phase gate or the generation of non-classical states of light. The standard nonlinearities in conventional optical media are however too weak to induce such effects. One approach to create single-photon nonlinearities is to temporally convert the photons into dark-state polaritons involving Rydberg atoms[1]. The principle is that a single Rydberg excitation may modify strongly the susceptibility of a small region, thanks to Rydberg blockade[2].

Recent experiments, implemented in an ultracold cloud of ^{87}Rb atoms held in an optical dipole trap, demonstrated nonlinearities at the quantum level, such as it creates a medium transparent for single-photons, but is absorptive for photon pairs[3, 4]. This effect was used to create an attractive potential between photons [5] and single-photon switches [6, 7].

Here, our atomic cloud is placed into a one-ended low finesse optical cavity which increases the light-matter coupling and translates a nonlinear dispersion into a shift of the cavity resonance[8]. One can also work close to the impedance matching conditions, such as a Rydberg excitation could induce a π-phase shift on a photon.

Our setup includes also the possibility to perform second-order correlation measurements and homodyne detections of the outgoing field[9].

We will present the intracavity nonlinear absorptions we observed, with a comparison to our theoretical models. Then, with some improvements on the setup, we aim at observing bunching or anti-bunching of light and phase jumps induced by Rybderg excitations in our intracavity cloud.

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Simple criteria for noise resistance of two qudit entanglement

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Too much noise kills entanglement. This is the main problem in its production and transmission. We use a handy approach to indicate noise resistance of entanglement of a bi-partite system described by $d \times d$ Hilbert space. Our analysis uses a geometric approach [1] based on the fact that if a scalar product of a vector $\vec{s}$ with a vector $\vec{e}$ is less than the square of the norm of $\vec{e}$, then $\vec{s} \neq \vec{e}$. We use such concepts for correlation tensors of separable and entangled states. As a general form correlation tensors for pairs of qudits, for $d > 2$, is very difficult to obtain, because one does not have a Bloch sphere for pure one qudit states, we use a simplified approach. The criterion reads : if the largest Schmidt eigenvalue of a correlation tensor is smaller than the square of its norm, then the state is entangled. this criterion is applied in the case of various types of noise admixtures to the initial (pure) state. These include white noise, colored noise, local depolarizing noise and amplitude damping noise. A broad set of numerical and analytical results is presented. As the other simple criterion for entanglement is violation of Bell's inequalities, we also find critical noise parameters to violate specific family of Bell inequalities (CGLMP)[2], for maximally entangled states. We give analytical forms of our results for d approaching infinity.

The details can be found in Ref. [3].

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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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Quasiparticle dynamics in a superconducting atomic contact

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Although bulk superconductors consist in an assembly of delocalized and overlapping pairs of electrons, the Cooper pairs, localized states arise at atomic-size contacts [1]. The occupation of these fermionic states with 0, 1, or 2 quasiparticles was detected using circuit quantum electrodynamics techniques [2], with a continuous measurement almost at the quantum non-demolition (QND) limit. One observes quantum jumps between states with 0 and 2 quasiparticles, which correspond to the two possible states of a localized Cooper pair. In addition, the trapping of out-of-equilibrium quasiparticles from the superconducting electrodes induces frequent parity changes (transitions between 0 and 1, or 1 and 2). The rates of the corresponding processes are extracted from continuous measurements, using a hidden markov model toolbox.

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Quantum Communication - QCOM

Bounds on entanglement distillation and secret key agreement capacities for quantum broadcast channels

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The squashed entanglement of a quantum channel finds application as an upper bound on the rate at which secret key and entanglement can be generated when using the quantum channel a large number of times in addition to unlimited classical communication [1, 2]. This quantity has led to an upper bound of $\log((1+\eta)/(1-\eta))$ on the capacity of an optical communication channel for such a task, where η is the average fraction of photons that make it from the input to the output of the channel. In this work, we go beyond the single-sender single-receiver setting and consider a more general scenario involving a quantum broadcast channel between a single sender and multiple receivers. We establish constraints on the rates at which secret key and entanglement can be generated between any subset of the users of such a channel [3]. We do so by employing multipartite generalizations of the squashed entanglement [4, 5], while along the way developing several new properties of these measures. We apply our results to the case of an optical broadcast channel with one sender and two receivers, and characterize the rate-loss tradeoffs for such a channel.

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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.

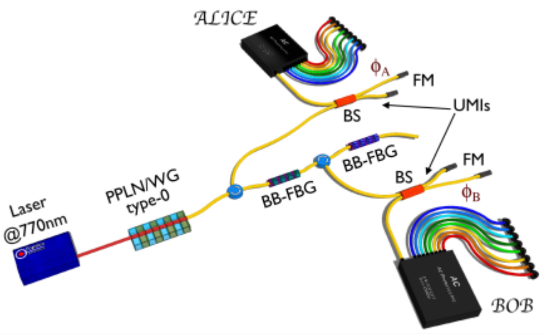

FIGURE 1. Experimental setup. A periodically poled lithium niobate waveguide (PPLN/WG) pumped by a laser at 770 nm emits pairs of energy-time entangled photons in the telecom band via the process of spontaneous parametric down-conversion (SPDC). The quasi-phase matched SPDC spectrum engineered towards 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.

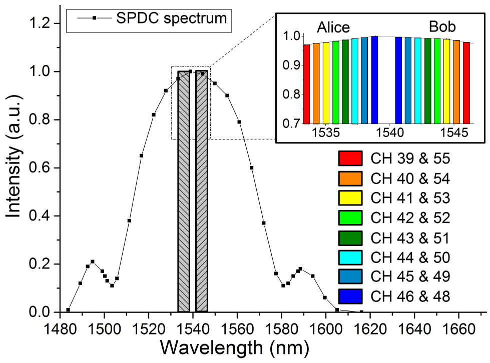

FIGURE 2. Spontaneous parametric down-conversion spectrum out of the PPLN/WG divided in pairs of standard telecommunication channels (ITU).

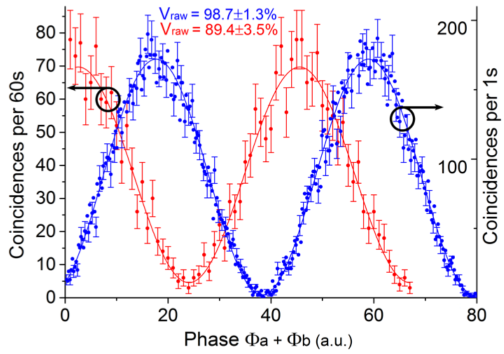

FIGURE 3. 2-photon interference as a function of the sum of the user's interferomters phases for 0 km and 150 km

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Extracting Randomness Against an Adversary with Memory Device

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Generating randomness is a task of both fundamental and practical interest. From a theoretical point of view, any deterministic theory can provide only apparent randomness, i.e. randomness due to a lack of knowledge of the systems involved. But quantum theory, being probabilistic, allows for intrinsic randomness. From an applied point of view, random bits are a valuable ressource for cryptography, randomized algorithms, or numerical simulations. It is therefore essential to be able to characterize and quantify randomness and to design secure protocols for creating random bits.

Guaranteeing that a bit - or a sequence of bits - a is random is a complicated task, and a common way to do so is by introducing an observer whose goal is to guess a. The probability with which the observer guesses correctly is called the *guessing probability* [1]. Depending on the assumptions made on the theoretical context, the devices and the power of the observer, one tries to upper-bound the guessing probability. As one can expect, there is a trade-off between the strength of the assumptions and the quality of the bound. The goal of this work is to compute the guessing probability while discarding several common assumptions.

First of all, our work is conducted in a *device-independent* manner [2]. A common problem of security proofs is that they are established by making strong assumptions on the internal working of the devices, that are hard to meet in experiments. These discrepancies between the theoretical requirements and the actual performances of the devices result in security loopholes. To solve this problem, one can use the quantitative links between randomness and non-locality (understood here as *amount of violation of a Bell inequality*). Indeed, the violation of a Bell inequality can be experimentally verified without making any assumptions of the internal working of the devices, and only by studying the correlations arising from these devices.

The second very common assumption that we discard is that of *independent and identically distributed* (i.i.d.) rounds. In an i.i.d. scenario, the guessing probability is computed for a single use of the devices and extended in a straightforward way to the case of n uses of the devices. However this is a strong limitation of the power of the observer [3]. In this work, we thus compute the guessing probability for an observer keeping tracks of everything that has happened in the previous rounds.

Finally, many information processing tasks are studied in the context of quantum theory. When it comes to device-independent protocols, this corresponds to taking into account only quantum correlations. But one can also study those tasks in a larger context, such as the one of *no-signaling* correlations [4]. Bounds obtained in this context are thus more trustworthy, because they would hold true even if quantum theory were to be proven wrong. This is why we consider here a supra-quantum observer with access to no-signaling correlations.

In this work, we quantify the randomness that one can extract in such a broad context, by computing the optimal guessing probability of the observer and finding actual strategies achieving this optimum. Our current results already show that providing the adversary with a memory gives an advantage, that is, reduces the amount of randomness that can be extracted. Our final aim is to answer the question of whether or not it is possible to extract randomness in such a general scenario.

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Floating bases quantum key distribution protocol with decoy states

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Among all promising areas of quantum technologies such as high-efficient information processing and ultra-sensitive metrology, exclusively quantum key distribution (QKD) systems reach a stage of device implementation and commercialization. Due to the fact of breaking of public-key encryption algorithms using quantum computing, QKD systems have attracted a great deal of interest. The foundation of security of public-key encryption algorithms is the complexity of several mathematical problems, *e.g.*, computing discrete logarithms and integer factorization. However, using the Shor's algorithm these problems are solvable in polynomial time.

Providing of a useful method for key distribution between two legal users, QKD systems change the paradigm of cryptography and restore the idea of the one-time-pad encryption. Security of a quantum key is guaranteed not by limitations of computational and technological resources of an eavesdropper, but fundamental laws : according to the no-cloning theorem, it is impossible to create an exact copy of a quantum object, and an eavesdropper cannot distinguish orthogonal states without their perturbations. Thus, QKD systems are not unbreakable, but they always allow to detect Eve.

Security of QKD systems is limited by the quantum bit error rate (QBER) and attacks on the channel. In turn, they are caused by imperfections of practical QKD systems. In practical QKD setups, weak coherent states $|\mu\exp(i\theta)\rangle$ with the mean number $\mu = 0.1{-}0.5$ of photons per pulse are used instead of true single photons. Since there is no reference phase, Bob and Eve have no information on the phase θ. According to the Poisson statistics, a non-negligible fraction of pulses contains more than one photon. This fact provides certain constrains for length of communication channels for QKD, which is limited by the photon number splitting (PNS) attack.

A promising approach is the decoy state protocol, in which Alice randomly sends some of laser pulses with a lower average photon number. These decoy states are used in the protocol to detect a PNS attack, because Eve has no way to verify is a pulse is signal and decoy.

Recently, a new QKD protocol with floating bases has been proposed [1]. In this approach, Alice and Bob use a previously shared auxiliary key k_0 to generate secret additional rotations $\Delta\varphi$ of BB84 bases. In other words, for ith signal state, Alice uses k_0 and a random function to generate rotation to BB84 bases as follows :

$$\Delta\varphi_i = \chi(i, k_0) \mod 2\pi. \tag{1}$$

It is important that function (1) with auxiliary key k_0 generates the uniform distribution over the circle. Thus, the crucial feature of this protocol is that it allows move away from fixed set of bases :

$$\hat{\sigma}_{y+\Delta\varphi} \equiv \{|\uparrow +\Delta\varphi\rangle, |\rightarrow +\Delta\varphi\rangle\}, \quad \hat{\sigma}_{x+\Delta\varphi} \equiv \{|\nearrow +\Delta\varphi\rangle, |\searrow +\Delta\varphi\rangle\} \tag{2}$$

In other words, this basis can float at any position on the circle. However, for floating bases QKD protocol problems related with the PNS-attack are still a challenge.

We present an extension of the QKD protocol with floating bases [1] by combining this approach with the basic version of the decoy states protocol [2]. We suppose that Alice has, first, previously shared with Bob an initial key k_0, which gives the uniform distribution over the circle, and, second, a random sequence k_d for choosing type of transmitted state : vacuum state with the mean number of photons μ_0, decoy state with the mean number μ_d, and signal state the mean number μ_s, We provide the security analysis of the suggested protocol and discuss its realization in experiments.

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Miniature Quantum Key Distribution sender add-on for handheld devices

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We present a complete free-space Quantum Key Distribution (QKD) solution for daily-life secure communication. We focus on a practical scenario where the user owns an integrated QKD module embedded in a mobile device, which allows him to generate a secure key with a trusted node. Potential applications entail wireless transaction, key generation for online authentication and quantum network interfacing. Although our system is optimised for short distance links, it can be easily adapted to long-distance schemes by adjusting the collimation or collection optics on each side.

The system we developed implements BB84-like protocols. It includes a miniature QKD sender unit (35 x 20 x 8 mm) emitting near-infrared polarised faint laser pulses at 100 MHz repetition rate. An additional bright visible laser is overlapped with the quantum signal to enable both synchronisation with the receiver and efficient beam tracking for continuous operation. An Android App controlls the integrated optics platform and performs post-processing as well as live basis alignment over a classical WLAN channel with the receiver's computer. First tests indicate that the first prototype features a mean photon number of $\mu = 0.013$ and that a secret key rate of 30 kHz should be obtained for handheld operation.

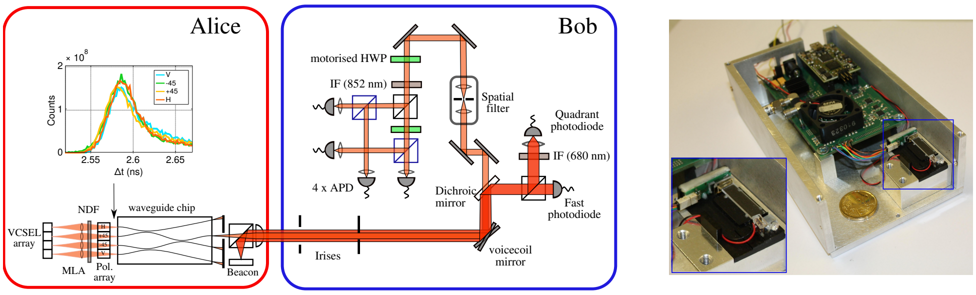

Figure 1: Short distance QKD protocol. Left: Optical set-up for the integrated sender unit and the receiver equipped with a beam tracking unit. Right: Picture of the complete sender unit, including the micro-optical assembly and the driving electronics.

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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.

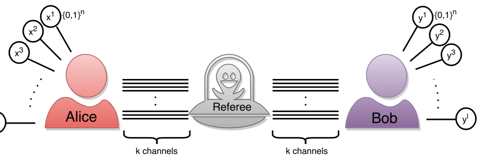

FIGURE 1. *l* Clients connected to servers Alice and Bob who communicate to the Referee via *k* cables

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.

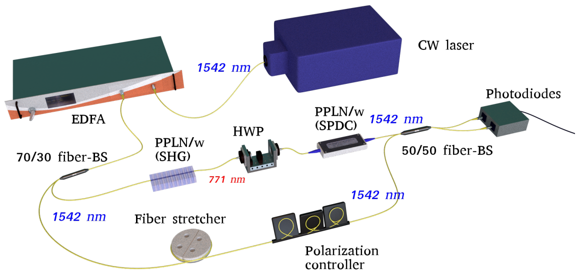

FIGURE 1: Experimental setup. EDFA, erbium-doped fiber amplifier ; PPLN/w, periodically poled lithium niobate waveguide ; SHG, second harmonic generation ; SPDC, spontaneous parametric downconversion

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.

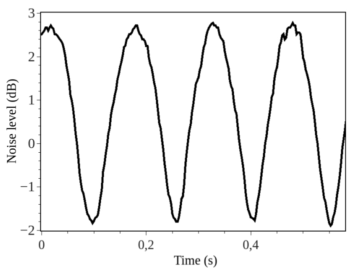

FIGURE 2: Normalized noise variances at 2 MHz of squeezed vacuum state as a function of the local oscillator phase.

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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Quantum Information Foundations - FOUND

Broadcasting of Quantum Correlations : Possibilities & Impossibilities

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In this work, we extensively study the problem of broadcasting of quantum correlations. This includes broadcasting of quantum entanglement as well as correlations that go beyond the notion of entanglement [1]. It is quite well known from the "No-Broadcasting theorem" that perfect broadcasting of quantum correlation is not possible [2]. However it does not rule out the possibility of partial broadcasting of correlations where we can get lesser correlated states from a given correlated state [3]. In order to have a holistic view of broadcasting, we investigate this problem by starting with most general representation of two qubit mixed states in terms of the Bloch vectors. As a cloning transformation we have used universal symmetric optimal Buzek-Hillery (B-H) cloner both locally and nonlocally [4]. In addition to the idea of broadcasting of entanglement for general two qubit mixed states, we explore broadcasting of quantum correlations that go beyond entanglement. Remarkably, we find that it is impossible to even partially broadcast such correlations. Lastly, we generalize this impossibility result for any symmetric or asymmetric cloning machines as well. This result brings out a fundamental difference between the correlation defined from the perspective of entanglement and the correlation measure which claims to go beyond entanglement.

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Complementarity in multi-beam interference experiments.

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We analyse the problem of complementarity relation in multi-beam interference experiments. We derive a duality relation between fringe visibility and which-way information for three slit interference set up[1]. For multi-beam set-up, instead of conventional notion of the wave nature of a quantum system, i.e., the interference fringe visibility, we introduce a novel quantifier as the normalized quantum coherence, recently defined in the framework of quantum information theory and therefore reached to a generalized wave-particle duality relation for multi-path quantum interference phenomena[2]. The particle nature is quantified by the path distinguishability or the which-path information based on unambiguous quantum state discrimination. We show that, the Bohr complementarity principle, for multi-path quantum interference, can also be stated with a duality relation between the quantum coherence and the path distinguishability. For two-path interference, the quantum coherence is identical to the interference fringe visibility, and the relation reduces to the well-know complementarity relation. The new duality relation continues to hold in the case where mixedness is introduced due to possible decoherence effects. The generalized wave-particle duality relation is shown to be reducible to the duality relation of fringe visibility and which-way information for three slit interference, derived independently.

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Detecting nonlocality in many-body systems with two-body correlators

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Nonlocality is the property of quantum correlations of going beyond a description in terms of local realism [1]. More specifically, correlations between spatially separated observers are said to be nonlocal when they cannot be simulated by classical systems sharing correlated random variables. This feature can be detected by means of the so-called Bell inequalities.

Together with entanglement [2], nonlocality constitutes a key resource in many information-processing protocols in the fast developing field of quantum information. Furthermore, entanglement has proven to be very useful in the study of many-body systems and the nature of quantum phase transitions [3].

Interestingly, while we are able to completely characterize these features when only two observers are involved (i.e. in a bipartite scenario), much less is known if we take into account the presence of more than two parties. It is clear, though, that both nonlocality and entanglement exhibit a much richer structure in the multipartite setting. Remarkably, nonlocality and entanglement were proven to be inequivalent features of quantum states, since the former is actually a stronger property than the latter.

In this work we address the question of whether nonlocality can be exploited to get a better understanding of correlations in many-body systems. Moreover, we approach the problem by supposing one has a limited amount of information about the system, that is, knowledge of one- and two-body correlations only. It has already been shown that it is possible to construct valid Bell inequalities expressed in terms of up to two-body correlators, for an arbitrarily large number of parties [4]. More importantly, these inequalities can be violated by physically relevant many-body quantum states.

Our work is a continuation along this line, aiming to approach the problem from a more general set of correlations, namely the no-signalling ones. Since quantum correlations satisfy the no-signalling principle, the quantum set constitutes a subset of the no-signalling one, but the latter is known to be easier to characterize. Our goal is thus to study the structure of the no-signalling set in the space of one- and two-body correlators only.

The main motivation is to understand to what extent is possible to study nonlocality with two-body correlators when one is provided with such partial knowledge of the correlations in the system. In particular, we are interested in investigating which kind of multipartite nonlocality is detectable with up to two-body correlators only. Moreover, the results of our study would have also practical relevance. Indeed, requiring to have access only to few-body correlators helps reducing the technical challenges one encounters when performing a Bell-type experiment with many-body systems.

We have succeeded in characterizing the two-body no-signalling set in the case of three and four parties, and it is clear from our results that there are no-signalling correlations exhibiting genuine multipartite nonlocality that can be detected by studying the two-body reduced space. We therefore hope that our work can lead to the possibility of witnessing genuine multipartite nonlocality with one- and two-body correlators for any number of parties.

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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].

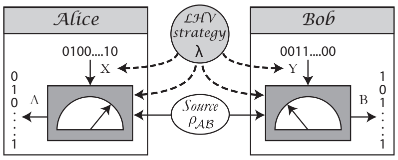

FIGURE 1. Standard quantum correlation measurement scheme, in the presence of a local hidden variable (LHV) strategy. Two users, Alice ($\mathcal{A}$) and Bob ($\mathcal{B}$), each have a measurement apparatus. These devices each take a binary input (x,y) and return a binary output (a,b). They can also 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.

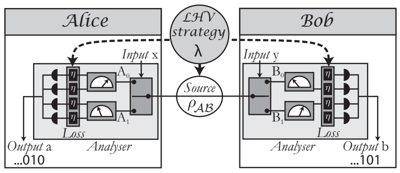

FIGURE 2. Two boxes receive each a particle, emitted by a common source. They are given inputs x and y, which we depict here as the setting of an active switch, and return outputs a and b, respectively. There is the possibility for non-detection events, in which case the corresponding output variable 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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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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YQIS 2015: Relations between quantum walks and lifted random walks

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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 are a non-quantum extension proven to deliver that speedup [2]. 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. As a first step in this contribution we highlight some similarities between the two procedures, elaborated on examples like the cycle and torus graphs - graphs used previously to illustrate the acceleration of quantum walks. This shows how the two acceleration schemes are closely related and can in fact learn from each other.

First, given a lifted walk quadratically improving the mixing time, we propose a straightforward yet unexplored quantization of it. By demanding unistochasticity of the lifted walk, a condition obeyed by all known examples, there must be a unitary matrix (i.e. quantum walk) constructible by simply rooting the lifted walk's probabilities and adding phases. The obtained quantization does not necessarily inherit the quadratic speedup for the general quantum walk mixing paradigm; nonetheless, it does so for the so-called open quantum walks, recently proposed by Attal et al. [3]. On top of that, we show some examples on which an additional speedup to the lifted walk can be attained. We thus present the apparently new result: *open quantum walks can speed up mixing*, both quadratically w.r.t. random walks and by a constant factor w.r.t. lifted walks. In addition, and in the spirit of our main goal, we show how open quantum walks can generally be implemented as an extended form of lifted walks. That is, they can be classically implemented in a local and efficient way. Using the latter construction, we find that the open quantum walk, by keeping some local degrees of freedom coherent in the quantum domain, naturally introduces a classical feedback-like extension to the lifted walk.

In the other direction, we pose the question of whether the construction of quantum walks requires the same (**NP**-hard) information as is the case for lifted walks. We know lifted walks make use of multi-commodity flows on the graph to construct an efficient routing of probability. Whether the mixing of quantum walks relies on a similar principle is currently unknown. We now present a first indication that they do. We show that a principle, at the heart of lifted walks, might also be applicable to quantum walks. The principle, as proposed by Diaconis and Miclo [4], says: *It is always possible to speed up mixing by introducing momentum*. We show how the introduction of a similar momentum, incorporating the graph structure, to a given quantum walk can improve its mixing time. With this result we further underpin the observation made by Chandrashekar et al. [5] concerning quantum walk mixing time, and dare to pose it more boldly: *Unbalanced coins make quantum walks faster*.

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Thermalization hypothesis in Rydberg 1D gases: analytical study and test of its validity

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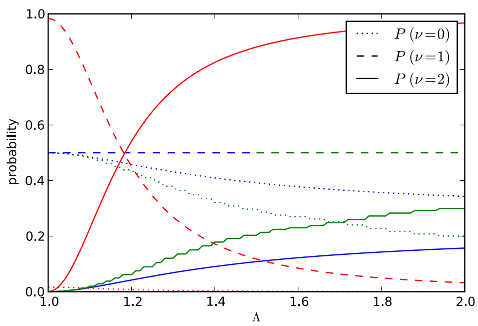
An atomic ensemble optically driven on a transition towards a Rydberg level exhibits complex many-body dynamics, due to the induced strong dipole-dipole interactions. In particular, these interactions prevent two atoms from being simultaneously excited to their Rydberg state when located close to each other. This phenomenon, the Rydberg blockade, is a key ingredient in many atomic quantum-information proposals [1].

This blockade induces a spatial structuration of Rydberg excitations in the atomic sample. The exact computation of this structure is impossible, and two approximations are often used in theoretical analyses: *1. sharp blockade radius:* the Rydberg blockade is assumed to forbid the simultaneous excitation of two atoms if they are closer than a given distance (the Rydberg radius R_b), while it has no influence at longer distances; *2. thermalization:* after a long enough time, even without any dissipative dynamics [2, 3], the system approximately ends up in a quasi-thermal state which is the equally weighted statistical mixture of all allowed ensemble states.

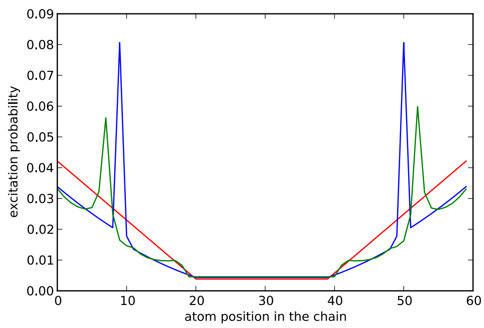
In this work, we keep the first assumption (sharp blockade radius) to study the dynamics of a dense 1D few-R_b-long atomic chain and test the validity of the second approximation (thermalization). We provide an analytical description of the emergent excitation lattice in the thermalization framework, giving the number $\mathcal{N}(\nu) = \frac{N^\nu}{\nu!}\left[1 - \frac{\nu-1}{\Lambda}\right]_+^\nu$ of configurations with ν excitations for N atoms along a line of length ΛR_b, as well as their spatial distribution. It agrees closely to previous results obtained through a Monte Carlo approach [3].

A numerical diagonalization of our system's Hamiltonian ($N = 100$), however, allows us to show noticeable differences in the excitation number probability as well as the spatial distribution of Rydberg excitations compared to the thermalization hypothesis. A 5-dimensional toy-model of the system confirms that these differences are not a numerical artifact.

This suggests that thermalization assumption should be considered with great care.



Probability to have ν excitations for $1 \leq \Lambda \leq 2$ with (red) and without (numerics:green, toy-model: blue) thermalization.



Spatial distribution of excitations for $\Lambda = 1.5$ with (red) and without (numerics:green, toy-model: blue) thermalization.

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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)-based source that generates nonmaximally polarisation-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 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 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 close the locality loophole. 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

A Nanofiber-based Memory for Light

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Developing light-matter interfaces is a crucial capability with unique applications to quantum optics and quantum information networks. In this context, our group focuses on the development of quantum memories in cold, neutral atom clouds, using both electromagnetically-induced transparency (EIT) and DLCZ as interacting schemes [1]. We recently reported for instance the quantum storage of qubits encoded in the orbital angular momentum degree of freedom [2]. Here, we demonstrate [3] for the first time EIT and optical storage at the single-photon level for the light tightly guided by a subwavelength-diameter optical fiber, *aka* nanofiber. In a nanofiber, the guided photons are highly confined and the majority of the light power travels in the evanescent field outside the glass. This new setting is a promising alternative to free-space focusing, which limits the interaction one can obtain, and provides a novel platform for developing all-fibered quantum networks.

Our experimental setup consists of a cold cesium cloud overlapped with an optical nanofiber in a ultra-high vacuum chamber. The cesium cloud is in free expansion after being released from a magneto-optical trap (MOT). To first characterize this system, we sent a probe beam through the nanofiber and observed EIT when shining a control laser beam on the atom cloud in free-space outside the nanofiber.

After having demonstrated transparency, we implemented a memory protocol based on dynamic EIT in the single-photon regime. Measurements are done at the fiber output using a single photon detector and reconstructing the histogram of photon arrival times after many repetitions of the experiment. The input signal pulse enters the atomic cloud in EIT regime. When the pulse is inside the atomic cloud, the control beam is shut off. Part of the optical pulse is stored in a collective state of the atomic ensemble. The pulse is then retrieved after a variable storage time by switching back on the control beam. Overall storage and retrieval efficiency $\eta = (10 \pm 0.5)\%$ is demonstrated. The decay of the retrieval efficiency is at a few microsecond scale, limited here by the residual magnetic field and the finite atomic temperature.

This novel capability based on the interaction of the evanescent part of the guided mode with the surrounding atoms provides an intrisically fibered memory. The next step will be the combination of the reported scheme with the dipole trapping of atoms close to the fiber surface as demonstrated in [4] with large optical thickness and longer coherence time.

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Coherent Population Oscillations based storage

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Optical memories have become a very active research topic in the area of quantum information processing and quantum communication. Different storage protocols have been developed in atomic systems, such as Electromagnetically Induced Transparency (EIT) [1] or Gradient Echo Memory [2]. Most of the methods under consideration are based on the excitation of a coherence between atomic levels. As a consequence, they can only be efficiently implemented in systems where this coherence has a long liftetime, and are very sensitive to dephasing effects.

Last year, we demonstrated a new storage protocol based on long-lived Coherent Population Oscillations (CPO), in hot metastable helium vapor [3]. CPO-based storage was also recently performed with cesium atoms at room temperature [4]. CPO occurs in a two level system (TLS) when two coherent electromagnetic fields of different amplitudes drive the same transition. The light beats modulate the population difference between the two levels and open a transparency window in the absorption profile of the weak field, limited by the decay rate of population of the upper level. As a population effect, CPO is usually not considered as a phenomenon that could be used to store a light field. Nevertheless, a first theoretical paper about CPO-based storage was published by an Israeli group [5]. They study the phenomenon in a TLS that decays via a shelving state, in order to increase the lifetime of the memory. In our group, we focus in a Λ-system composed of two coupled TLSs, which gives rise to an ultranarrow CPO resonance due to the transfer of CPOs to CPOs between the lower states of the Λ-system [6]. Less losses and higher storage efficiencies are expected in such a system and we have experimentally demonstrated that it is phase preserving. Simulations based on optical Bloch equations and wave propagation equations are used to model this phenomenon.

As CPO-based storage does not involve any atomic coherences, it has the advantage of being robust to dephasing effects such as small magnetic field inhomogeneities.

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

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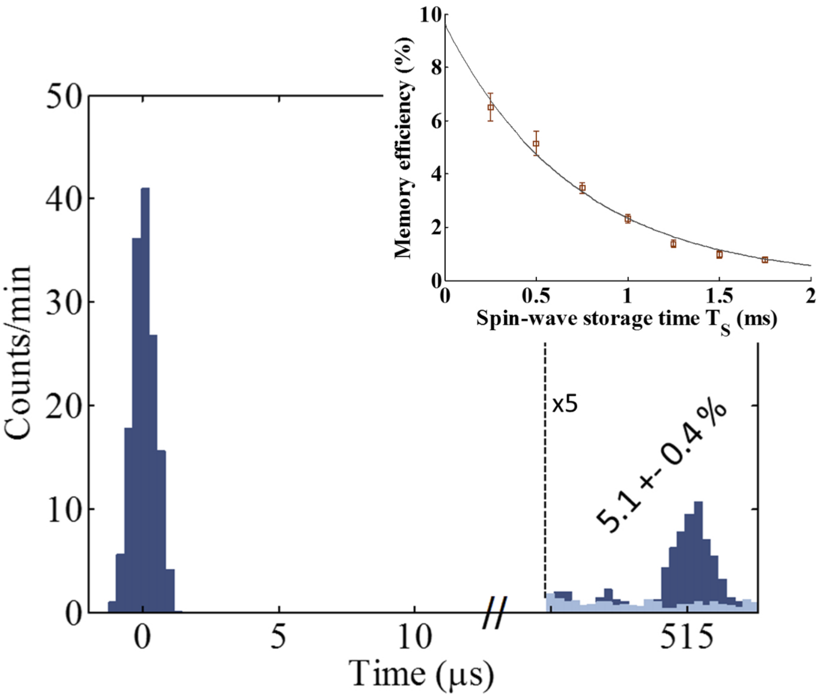
Efficient and long-lived memories are key devices in the development of long-distance quantum communication. DLCZ-type quantum repeaters, for instance, require the possibility to store and retrieve a state on demand. Long-lived storage can be realized by storing the light as spin excitations. However, 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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Evolution of phase of the retrieved pulse in EIT storage

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Electromagnetic induced transparency (EIT) is nowadays considered to be a useful protocol for quantum storage in various physical systems such as cold atoms, gas cells, doped crystals, etc [1]. It relies on the long lived Raman coherence between the two ground states of a Λ system and is associated with a strong change in the dispersion properties of the medium. Due to the presence of a strong coupling beam on one arm, a narrow transparency window is opened for a weak probe on the other arm. After entering the medium, the probe pulse can be stored in the ground state coherences by switching off the coupling beam and retrieved by switching it on. Recent experiments have been performed in an optically detuned configuration called the Raman storage protocol [2].

In the present work, we report on the time evolution of the phase shift of the retrieved pulse with respect to the coupling, when the storage is achieved with an optically detuned coupling beam [3]. We perform storage (Fig. 1(a)) in Λ system in metastable helium (He) based on $2^3S_1 \rightarrow 2^3P_1$ transition. Using homodyne detection, we measure the relative phase between the coupling and probe during storage and retrieval steps. We have found that the relative phase between the incident and the retrieved pulse increases with optical detuning and evolves with time during the retrieval step (Fig. 1(b)). We have performed numerical simulations of Maxwell-Bloch equations taking into account the propagation, storage and retrieval of the probe pulse, which are in good agreement with the experimental data. The physical explanation of the phase shift is that it originates from the dispersive propagation of the pulse in the medium under EIT conditions. We believe that the existence of the time dependent phase shift is of particular importance for light storage in far detuned regime [2].

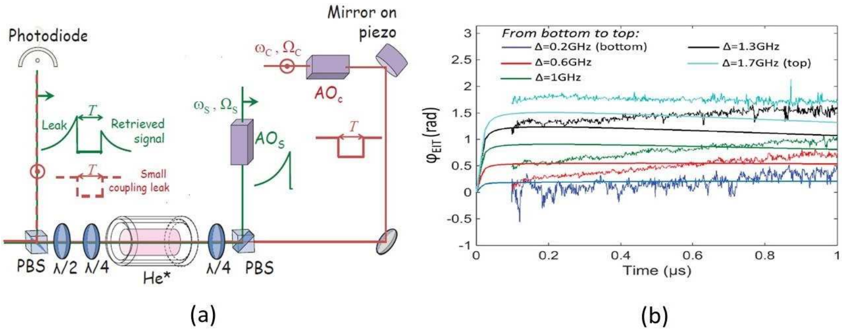

FIGURE 1. (a) Schematic of the set up, the coupling (Ω_c) and the probe (Ω_s) are derived from the same laser, their frequency and amplitude are controlled by two acousto optics (AO) and are recombined using a polarizing beam splitter (PBS) before the He* cell. The polarization optics after the cell allows detection of mainly the probe along with a small residual coupling which acts as a local oscillator to perform homodyne detection using a piezo-electric transducer attached to a mirror in its path. (b) Experimental data and simulations (solid lines) for the temporal evolution of the extra phase shift $\varphi_{EIT}(t)$ for different optical detunings Δ during the retrieval step.

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Non-classical correlations between a C-band telecom photon and a spin wave in an atomic ensemble quantum memory

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Quantum memories (QM) are building blocks of quantum repeater architectures allowing long distance quantum communication. They provide an interface between stationary quantum bits (encoded in atom-like systems) and flying qubits (encoded in photons). We use an ensemble of laser cooled ^{87}Rb atoms as a QM following the quantum repeater scheme proposed by Duan, Lukin, Cirac and Zoller (DLCZ) [1]. An incoming pulse creates a single collective spin excitation via a Raman transition, heralded by the scattered write photon. After a programmable storage time, the QM can be read out detecting the correlated read photon. In a realistic fiber-based quantum network, flying qubits should be encoded on telecom photons, for which fiber transmission is the highest. However, most of the long-lived quantum memories absorb and emit photons in the visible range, where losses in optical fibers are significant.

To overcome this limitation, Quantum Frequency Conversion (QFC) to telecom wavelength at 1367 nm has been demonstrated using four wave mixing in an ultra dense atomic ensemble [2]. Our approach is to use non-linear waveguides as efficient QFC to convert photons at 780 nm to 1552 nm. A proof of principle of combination between the DLCZ memory and frequency conversion interface has been implemented successfully in our group [3], converting the heralded read photon to the telecom C-band. However for quantum repeater applications storage need to be heralded by a telecom photon. In this work the write photons are converted and herald single collective spin excitations. We measure cross correlation function between the C-band telecom photons and read photons and show that it is above the quantum limit. Our interface is based on a PPLN waveguide where the single photons at 780 nm emitted by the atomic ensemble interact with a pump laser via Difference Frequency Generation, creating 1552 nm photons. The main drawback of the QFC is the Raman noise created by the pump light in the waveguide. Thanks to a proper narrowband filtering of this noise, the QFC shows high signal-to-noise ratio at single photon level, ensuring the conservation of the non-classical correlations between the converted telecom photon and the spin-wave, for storage time up to 40 us.

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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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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.

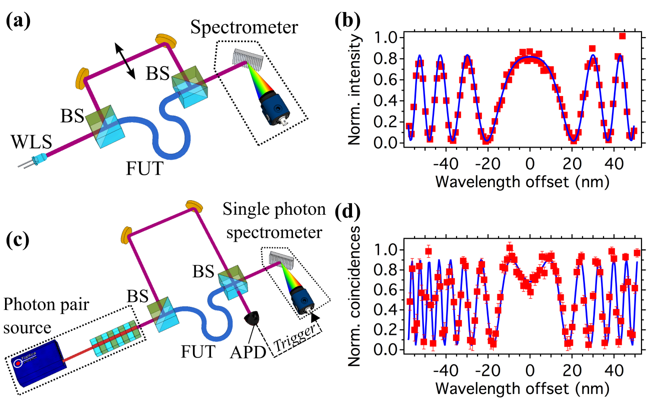

FIGURE 1: (a) Classical WLI setup for CD measurements. WLS : white light source, BS : beam-splitter. (b) Classical results. A wavelength offset of zero corresponds to 1561 nm. (c) Entanglement-based setup. (d) Results in the quantum regime.

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 Coherence Sets The Quantum Speed Limit For Mixed States

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Quantum coherence is a key resource like entanglement and discord in quantum information theory. Wigner-Yanase skew information, which was shown to be the quantum part of the uncertainty, has recently been projected as an observable measure of quantum coherence. On the other hand, the quantum speed limit has been established as an important notion for developing the ultra-speed quantum computer and communication channel. Here, we show that both of these quantities are related and thus, cast coherence as a resource to control the speed of quantum communication.

Here, We derive a tighter and experimentally measurable Mandelstam and Tamm kind of QSL for unitary evolutions with time independent Hamiltonians

$$\tau \geq \frac{\hbar}{\sqrt{2}} \frac{\cos^{-1} A(\rho_1, \rho_2)}{\sqrt{Q(\rho_1, H)}} = \mathcal{T}_l(\rho_1, H, \rho_2). \tag{1}$$

The time bound in Eq. (1) can easily be generalized for time dependent Hamiltonian $H(t)$. For a time dependent Hamiltonian $H(t)$, the inequality in (1) becomes $\tau \geq \frac{\hbar}{\sqrt{2}} \frac{\cos^{-1} A(\rho_1,\rho_2)}{\overline{\sqrt{Q_\tau(\rho_1,H(t))}}}$, where $\overline{\sqrt{Q_\tau(\rho_1, H(t))}} = \frac{1}{\tau}\int_0^\tau \sqrt{Q(\rho_1, H(t))}dt$ can be regarded as the time average of the quantum coherence or quantum part of the energy uncertainty. Thus, we set a new role for quantum coherence or asymmetry as a resource to control and manipulate the evolution speed. We also compared and showed that our bound is tighter than various existing bounds.

An important question in the study of quantum speed limit may be how it behaves under classical mixing and partial elimination of states. This is due to the fact that this may help us to properly choose a state or evolution operator to control the speed limit. In this paper, we try to address this question and show that the product of the minimal time of quantum evolution and the quantum part of the uncertainty in the evolution Hamiltonian H decreases under classical mixing. We already know how quantum coherence behaves under classical mixing. This new relation gives an insight to the quantum speed limit and shows how it behaves under classical mixing.

This inequality naturally raises another fundamental question: How does the quantum speed limit of a system behave under partial elimination of states of the system? We show that the product of the time bound of the evolution and the quantum part of the uncertainty in energy or quantum coherence or asymmetry of the state with respect to the evolution operator decreases if a part of the system is discarded.

We show that our bounds can further be generalized for completely positive trace preserving evolutions.

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Quantum Simulation & Processing - QSP

Algorithmic Cooling in Liquid State NMR

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Heat-bath algorithmic cooling (HBAC) [1–3] employs thermalization to purify quantum systems that interact with a heat bath, such as ensembles of nuclear spins, or cold atoms in an optical lattice. When applied to spins, HBAC produces ensembles of highly polarized spins, which enhance the signal strength in nuclear magnetic resonance (NMR). According to this cooling approach, spin-half nuclei in a constant magnetic field are considered as bits, or more precisely quantum bits, in a known probability distribution. Algorithmic steps on these bits are then translated into NMR pulse sequences using common NMR quantum computation tools. The algorithmic cooling of spins is achieved by alternately combining reversible, entropy-preserving manipulations (borrowed from data compression algorithms) with selective transfer of entropy from spins to the environment (for a recent review of HBAC see Ref. [4]).

HBAC, and multi-cycle HBAC, were previously achieved with nuclear spins using solid-state nuclear magnetic resonance (NMR), where spin diffusion allowed some spins to relax much more rapidly than others [6, 7]. In the liquid state, a partial variant of HBAC, without entropy compression, was applied to the three qubits of 13C-enriched trichloroethylene, resulting in modest cooling of the spin system [5]. Recently, we utilized (following [7]) gradient ascent pulse engineering (GRAPE), an optimal control algorithm [8], to generate pulses with high fidelity for the compression and polarization exchange (SWAP) gates [9]. Here, we combine those pulses to implement HBAC on this 3-spin system. Various cooling algorithms were applied, cooling the system beyond Shannon's entropy bound in several different ways. In particular, in one experiment a carbon qubit was cooled by a factor of 4.61.

This work is a step towards potentially integrating HBAC and other tools of NMR quantum computing into in vivo magnetic resonance spectroscopy [10, 11].

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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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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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MIXED DISORDER AND ITS EFFECT ON OPTOELECTRONICS PROPERTIES OF $GaAs/Al_xGa_{1-x}As$ SUPERLATTICES

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Abstract

Theoretical analysis of mixed disorder (association between topological and structural disorder) on resonance energy and miniband structure formation for rectangular GaAs/AlxGa1-xAs superlattices is presented in this studies. The Airy functions model based on the transfer-matrix technique with the assuming of the effective mass approximation and using Bastard's boundary conditions are applied to Schrodinger's equation for an asymmetric potential. A detailed analysis of the resonance energy and miniband formation is given.

The transmissions spectra reveal the appearance of a miniband structure with a concomitant disappearance of the localized states. The possibility of the creation of resonant states, with a good control of the energy differences is pointed out. Also the high bias voltage led to the emergence of a phase transition from the metallic state to the insulating.

The results show that for structures with short range correlation and stronger disorder, the electronic states of the system are delocalized since the localization length is greater than the system size. The quantum states in the well play a key role in the transmission.

Compared to other types of disorder structures already studied by the authors [1-2], we have shown in this study that the mixed disorder which is a combination between topological and structural disorder, gives the miniband that resists well to low applied bias voltages.

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Quantifying high dimensional entanglement with cameras and lenses

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Entanglement has long been recognized as the fuel that takes quantum communication beyond the classically possible. It finds application in secure key distribution [1], super-dense coding [2] and improves communication capacities in a general sense [3].

So far most implementations rely on two photonic degrees of freedom, limiting the capacity of each exchanged photon to one bit of information. Recent technological progress however allows to unlock the high dimensionality of spatial entanglement in photon pairs emerging from down-conversion processes. Two prominent examples are path entangled photons in waveguides [4–7] and access to the entangled angular momentum of photon pairs [13–16]. Such high dimensional entanglement endows each photon pair with more shared information, greatly improving the efficiency of known protocols [8–12] and enabling quantum communication at noise levels that would be prohibitive for qubit system.

A lot of attention has been devoted to proving entanglement for such high dimensional systems [17], revealing the underlying dimensionality of entanglement [6, 14, 16] or generally characterizing the potential for accommodating many degrees of freedom [18]. These initial investigations reveal the clear potential of the underlying systems, but in order to properly quantify the the advantage provided one needs to actually quantify the number of entangled bits (e-bits) shared by the photons. This is a notoriously difficult task in general and even at full access to a reconstructed density matrix there is no known method for computing this number in an efficient way (the best known is exponential in the system's dimension [19]).

While entanglement witnesses in general only provide an answer to the question whether a given state exhibits entanglement [20], their actual value can also be used to quantify the amount of entanglement [21–24]. Unfortunately even the simplest witnesses in this context require a number of measurement bases that scales with the system size, thus increasing the complexity rapidly with a growing number of degrees of freedom. Using mutually unbiased bases on the other hand provides a means of revealing entanglement with just two local measurements [26], a fact that has also been exploited for high dimensional experiments [27, 28].

In this work we combine the advantage of both approaches and quantify high dimensional entanglement purely from correlations in two mutually unbiased bases (MUBs). As an exemplary system we showcase how simple cameras and Fourier lenses can be harnessed to reveal the spatial correlations in down-conversion photons. After treating the bipartite case we move on to multipartite systems and show how to quantify multipartite entanglement using two local mutually unbiased settings.

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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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Quantum walks and gauge fields

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Quantum walks (QWs) are a particular class of quantum transport of a spin 1/2 particle on a spatial lattice. On the one hand, QWs are currently seen as universal bricks of quantum algorithms (based on qubits) [1], which enable to carry out some specific tasks, such as prime number factorization [2] or search in a data base [3], faster than classical algorithms (based on classical bits), provided that they are implemented with actual qubits *i.e.* with a quantum computer. On the other hand, QWs can be used for quantum simulation, which consists in reproducing the behaviour of a given quantum system, that may exist in Nature, such as electrons in metals, with another quantum system that we can engineer and control.

We will now focus on the discrete-time version of QWs (DTQWs). At each time-step of a one-dimensional DTQW, the spin of the walker is rotated through a so-called coin operator (in analogy with the coin tossing of a classical random walker), and the walker then undergoes a spin-dependent position shift to the left or to the right. This evolution naturally entangles the spin and the position of the walker. This one-step evolution is then repeated, and leads in essence to propagation phenomena with interferences. See [4] or [5] for an introduction to QWs.

The work of our group is theoretical and deals with the coupling between a single (discrete-time) quantum walker and interaction fields (gauge fields), which modify its spreading. Gauge fields can be seen either from a fundamental (the 4 interactions present in Nature), or from an effective point of view (they may model topological features of the graph on which the walker spreads). We have presented $1D$ DTQWs coupled to *arbitrary* electric and relativistic gravitational fields (curved space-time) [6], and $2D$ DTQWs coupled to arbitrary electromagnetic fields [7]. Also, we have built Landau levels for our $2D$ magnetic walk [8]. Our guideline to study these walks is their continuous limit *i.e.* when the step of the space-time lattice goes to zero. In such a limit, these walks reproduce the standard dynamics of Dirac fermions coupled to the above-mentioned fields. Interestingly, we have extended the interpretation of the electromagnetic gauge field outside the continuous limit, by showing that the corresponding walk exhibits a local $U(1)$ gauge invariance *on the lattice* (not only in the continuum). We can thus identify a discrete version of the electromagnetic tensor and conserved currents on the lattice. Eventually, this enables us to write down discrete Maxwell's equations and thus to give the gauge field a dynamics on the lattice.

Experiments have been realized which show the propagation of a $1D$ (*resp.* $2D$) quantum walker under the influence of a synthetic constant electric (*resp.* magnetic) field, with cold atoms in an optical lattice [9] (*resp.* with 3D integrated photonics [10]).

In my poster, I will present our last paper [7], on the electromagnetic $2D$ quantum walk.

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Standard and Sequential Measurement-Based Quantum Computation in non-ideal conditions

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One-way quantum computation relies on a cluster state of several entangled qubits as its primary resource: once prepared, measurement-based quantum computation (MBQC) is carried out via local measurements on its individual qubits only. While versatile — requiring only controlled-PHASE (CZ) gates for entanglement preparation, and local measurements for information processing — such entangled systems are elusive in naturally occurring systems and difficult to artificially manufacture. Consequently, the procurement of the cluster state itself is a major bottleneck to practical MBQC, especially considering that universality of computation requires cluster states composed of a huge number of qubits.

The difficulty in producing such states has stimulated the search for variants to standard MBQC, including ancilla-driven quantum computation [1], sequential MBQC [2], and just-in-time generation methods [3]. These variants take advantage of the fact that there is no need to produce the whole cluster at the beginning of the computation, rather only a handful of qubits is necessary, entangled at any one time via an alternating sequence of cluster generation and controlled measurement [4].

Here we focus on sequential MBQC. While the latter is equivalent to the standard MBQC under ideal conditions, it is not known if this equivalence holds in noisy environments, akin to those to be experienced in practical applications. To this end, we explore how standard and sequential implementations of the local teleportation of single qubit rotations, an essential operation for cluster computation, are affected by flaws in the preparation of the ancilla qubit and the implementation of the CZ gate. In addition, we address the local teleportation of the controlled-NOT gate under the effects of similar flaws, thus covering the minimum set of operations required for universal computation.

We model a flawed ancilla by setting a probability η that it is instead prepared in the maximally mixed state $I/2$, i.e. an otherwise perfect ancilla fed into a dephasing channel. For the CZ gate, we consider three possible scenarios: the conditionally applied phase factor is offset by an angle ϵ; there is a probability p that the two qubits are dephased, and transform into the state $I/4$; or, there is a probability s that the CZ gate does not act upon the two qubits. To quantify the effects of these flaws, we utilise the concept of gate fidelity [5] to directly analyse the overall operation's degradation. By a comparative analysis of the gate fidelity as a function of the parameters η, ϵ, p, s for standard and sequential approaches, we prove that the sequential model of local teleportation offers superior robustness against errors such as those we have accounted for. In addition, preliminary results will be presented that consider fault-tolerant implementations of sequential MBQC, where potential errors may be diagnosed and corrected/mitigated before they corrupt the final output.

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State and Process Tomography from Measurements along Quantum Trajectories

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This abstract describes ongoing works [8, 9] with L. Bretheau (ENS), Ph. Campagne-Ibarcq (ENS), I. Dotsenko (Collège de France), B. Huard (ENS) and P. Rouchon (Mines ParisTech).

Quantum tomography is usually based on positive operator-valued measure (POVM) and on their experimental statistics [6]. Among the available reconstructions, the maximum-likelihood (MaxLike) technique is a popular one. We propose an extension when the measurement process cannot be simply described by POVM. Here, the tomography relies on a set of quantum trajectories and their measurement records. It includes the fact that, in practice, each measurement could take a finite amount of time and could be corrupted by imperfections and decoherence. The proposed extension relies on effective matrices appearing in quantum smoothing [4, 5, 7, 10] and solutions of adjoint quantum filters. This provides an efficient computation of the likelihood function and its derivatives.

When the support of the likelihood function is mainly concentrated around its maximum, a good approximation of the Bayesian Mean estimate (see, e.g.,[2]) can be obtained by MaxLike estimation. It relies on the first terms of an asymptotic expansion of Laplace integrals [1]. Similar asymptotic expansion provides also a confidence interval, based on the Hessian of the likelihood function.

We focus here on process tomography, i.e. on parameter estimation: we detail the computation of the first and second derivatives of maximum-likelihood function, used in the optimization process, thanks to adjoint quantum filters. The derived algorithm is then tested on experimental data to estimate the detection efficiency for a superconducting qubit whose fluorescence field is measured using a heterodyne detector [3]. This estimate we provide goes with an uncertainty interval, reduced compared to the prior physical calibration.

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