*10th* *Colloquium* of the CNRS GDR № 3322 on Quantum Engineering, Foundations & Applications

Ingénierie Quantique, des aspects Fondamentaux aux Applications – IQFA

CNRS Headquaters, Michel-Ange Campus, Paris

November 13 - 15, 2019

---

# IQFA'X – Book of Abstracts

---

# Contents

# 1 What is IQFA ?

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

The **GDR IQFA**[1]**, "Ingénierie Quantique, des aspects Fondamentaux aux Applications"**, GDR № 3322 of the Centre National de la Recherche Scientifique (CNRS[2]), is a Research Network supported by the CNRS Institutes of Physics (INP[3]), Systems & Engineering Sciences (INSIS[4]), and Computer Sciences & their interactions (INS2I[5]), with which the quantum information community is mostly associated. This GDR gathers more than 50 French laboratories through which more than 90 teams are involved.

**The goal of the GDR IQFA is two-fold**: first, to establish a common base of knowledge, and second, to use this platform to emulate new knowledge.

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

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

**IQFA is organized along the 4 newly identified thematics - ART**[6] **-** that are currently highly investigated all around the world, and particularly with the next European Flaghsip project:

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

all surrounded by transverse Fundamental Quantum Aspects – Fqa.

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

## 1.2 Scientific Committee of the GDR IQFA

*Members:* Alexia Auffèves (CNRS, Uni. Grenoble Alpes),
Patrice Bertet (CEA, Uni. Paris Saclay),
Antoine Browaeys (CNRS, Inst. d'Optique Graduate School, Uni. Paris Saclay),
Thierry Chanelière (CNRS, Uni. Grenoble Alpes),
Eleni Diamanti (CNRS, Sorbonne Uni., Paris),
Anaïs Dréau (CNRS, Uni. Montpellier), Secretary,
Pascal Degiovanni (CNRS, ENS Lyon),
Iordanis Kerenidis (CNRS, Uni. Paris Diderot - Paris 7),
Tristan Meunier (CNRS, Uni. Grenoble Alpes),
Alexei Ourjoumtsev (CNRS, Collège de France),
Simon Perdrix (CNRS, Uni. de Lorraine Metz-Nancy),
Sébastien Tanzilli (Head, CNRS, Uni. Côte d'Azur),
Nicolas Treps (ENS Paris, Sorbonne Uni., Paris),

*Administration assistant:* Nathalie Koulechoff (CNRS, Uni. Côte d'Azur).

[1] French acronym for "Ingénierie Quantique, des aspects Fondamentaux aux Applications".
[2] http://www.cnrs.fr/
[3] http://www.cnrs.fr/inp/
[4] http://www.cnrs.fr/insis/
[5] http://www.cnrs.fr/ins2i/
[6] In French: Axes de Réflexion Thématiques.

# 2 IQFA'X Colloquium – Scientific Information

## 2.1 Welcome !

**IQFA'X** is organized by IQFA Scientific Committee members and by the CNRS Institute of Physics (INP[7]) at the CNRS Headquaters, campus Paris Michel-Ange.

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

- 7 tutorial talks, having a clear pedagogical purpose, on the very foundations and most advanced applications of the field, as well as 3 invited talks;
- 13 contributed talks on the current hot topics within the strategic thematics (ARTs) identified by the GDR IQFA (see online the ARTs[8] for more details);
- and 2 poster sessions gathering ∼60 posters, again within IQFA's strategic thematics (ARTs).

In total this year, **IQFA's Scientific Committee (see Sec. 1.2) has received 73 scientific contributions**.

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

We wish all the participants a fruitful colloquium.

**Anaïs Dréau** (IQFA's CS member & Secretary),
**Alexei Ourjoumtsev** (IQFA's CS member),
**Nicolas Treps** (IQFA's CS member),
& **Sébastien Tanzilli** (IQFA's Director),

*On behalf of* IQFA*'s Scientific Committee.*

[7]https://inp.cnrs.fr/
[8]http://gdriqfa.unice.fr/spip.php?rubrique2

### 2.2 Program of the colloquium

# Wednesday the 13th of November 2019

**09:00**
Welcome - S. Tanzilli & A. Lambrecht (CNRS/INP)

**09:30**
Tutorial - QCOM/QSIM - P. Senellart (CNRS, Univ. Paris Saclay, FR): *Pure quantum light generation in the solid-state*

**10:30**
Coffee break

**11:00**
Invited Talk - QCOM/QSIM - V. Parigi (Sorbonne Université, Paris, FR): *Continuous variables quantum complex networks*

**11:30**
QCOM - R. Parekh (Sorbonne Univ., FR & Indian Inst. Techno., Roorkee, IN): *Quantum protocol zoo*

**12:00**
QMET - E. Albertinale (CEA-Saclay, FR): *An irreversible qubit-photon coupling for the detection of itinerant microwave photons*

**12:30**
Lunch

**14:00**
Tutorial - QMET - S. Gröblacher (TU Delft, NL): *Quantum acoustic experiments*

**15:00**
QMET - V. Cimini (Univ. Roma, IT): *Tracking enzymatic activity with quantum light*

**15:30**
Coffee break

**16:00**
Invited Talk - QMET - S. Nascimbene (Collège de France, Paris, FR) : *Quantum-enhanced sensing using non-classical spin states of a highly magnetic atom*

**16:30**
QMET - R. Geiger (CNRS, Univ. PSL, Sorbonne Univ., FR): *High-sensitivity inertial measurements by cold-atom interferometry*

**17:00**
Poster session 1

# Thursday the 14th of November 2019

**09:00**
Tutorial - QCOM - T. Northup (Univ. Innsbruck, AT) : *Trapped ions for quantum networks*

**10:00**
QCOM - M. Schiavon (Univ. Padova, IT & Sorbonne Univ., FR): *Chip-based daylight quantum-key-distribution at 1550 nm*

**10:30**
Coffee break

**11:00**
Tutorial - QCOM - G. Ribordy (ID Quantique, CH) : *Quantum-safe cryptography, from research to industry*

**12:00**
QCOM - N. Sangouard (Univ. Basel, CH): *Self-testing - a trustworthy certification tool for quantum communications*

**12:30**
Lunch

**14:00**
Tutorial - QPAC - A. Montanaro (Univ. Bristol, UK) : *Quantum algorithms: an overview*

**15:00**
QPAC - P. Campagne-Ibarcq (Yale Univ., USA): *A fully stabilised logical quantum bit encoded in grid states of a superconducting cavity*

**15:30**
Coffee break

**16:00**
Tutorial - FQA - A. Acin (ICFO, Barcelona, ES): *Device-independent quantum information processing*

**17:00**
Poster session 2

**19:00**
Banquet

# Friday the 15th of November 2019

**09:00**
Tutorial - QPAC - J. Home (ETH Zurcih, CH) : *Quantum error correction in ion traps*

**10:00**
QPAC - B. Jadot (CNRS, Univ. Grenoble Alpes, FR): *Remote spin entanglement in semiconductor quantum circuits*

**10:30**
Coffee break

**11:00**
Invited Talk - QCOM - D. Efetov (ICFO, Barcelona, ES) : *2D material enabled quantum networks*

**11:30**
QCOM - D. Oser (CNRS, Univ. Paris-Saclay, FR): *High-quality entanglement on a silicon chip*

**12:00**
QPAC/QCOM - B. Pingault (Univ. Cambridge, UK): *Transform-limited photons from a long-lived tin-vacancy spin in diamond*

**12:30**
Lunch

**14:00**
FQA - S. Restuccia (Univ. Glasgow, UK): *Photon bunching in a rotating reference frame*

**14:30**
FQA - A. Peugeot (CEA-Saclay, FR): *Quantum microwaves with a dc-biased Josephson junction*

**15:00**
FQA - B. Pointard (IOGS, FR): *Quantum storage of one-photon and two-photon Fock states with an all-optical quantum memory*

**15:30**
Closing session - S. Tanzilli

### 2.3 The CNRS, the largest research organization in France

Created in October 1939, therefore celabrating this year its $80^{th}$ anniversary (see online CNRS, 80 ans[9]), the French National Center for Scientific Research, CNRS[10], (French: Centre national de la recherche scientifique) is the largest governmental research organisation in France and the largest fundamental science agency in Europe. It employs more than 31,700 staff members, including more than 11,1350 tenured researchers, 13,450 engineers and technical staff, as well as more than 7,100 contractual workers (among them, PhD candidates and post-doctoral fellows). It is headquartered in Paris and has administrative offices in Brussels, Beijing, Tokyo, Singapore, Washington D.C., Bonn, Moscow, Tunis, Johannesburg, Santiago de Chile, Israel, and New Delhi.

CNRS operates on the basis of research units (i.e., labs), which are of two kinds: "proper units" (UPRs) are operated solely by the CNRS, and "mixed units" (UMRs) are run in association with other institutions, such as universities, CEA, INSERM, etc. Members of mixed research units may either be CNRS researchers or university employees (associated professors or professors). Each research unit has a numeric code attached and is typically headed by a university professor or a CNRS research director. A research unit may be subdivided into research groups ("teams"). CNRS also has support units which may for instance supply administrative, computing, library, or engineering services.

In view of promoting multidisciplinary research thematics, **the CNRS is divided into 10 main institutes** (see online CNRS Institutes[11]):

- Institute of Chemistry (INC)
- Institute of Ecology and Environment (INEE)
- Institute of Physics (INP)
- Institute of Nuclear and Particle Physics (IN2P3)
- Institute of Biological Sciences (INSB)
- Institute for Humanities and Social Sciences (INSHS)
- Institute for Computer Sciences (INS2I)
- Institute for Engineering and Systems Sciences (INSIS)
- Institute for Mathematical Sciences (INSMI)
- Institute for Earth Sciences and Astronomy (INSU),

also holds a **"Mission for interdisciplinarity"** (see online CNRS MI[12]), and initiates "**Groupements de Recherche" (or research networks)**, such as IQFA, that network up and federate scientific communities in order to efficiently answer current scientific, technological, as well as societal thematics. Those thematics lie at the very core business of the CNRS institutes but can also emerge at the interfaces between two or several institutes.

The National Committee for Scientific Research, which is in charge of the recruitment and evaluation of researchers, is divided into 47 sections (e.g. section 41 is mathematics, section 7 is computer science and control, and so on). Research groups are affiliated with one primary institute and an optional secondary institute; the researchers themselves belong to one section.

The CNRS was ranked #3 in 2015 and #4 in 2017 by the Nature Index, which measures the largest contributors to papers published in 82 leading journals.

***Within the context of supporting scientific research & colloquiums, the CNRS, through its institutes of Physics, Information Science, & Engineering Sciences, supports and welcomes IQFA 'X colloquium at its headquarters.***

[9] https://80ans.cnrs.fr
[10] https://cnrs.fr/
[11] http://www.cnrs.fr/la-recherche
[12] http://www.cnrs.fr/mi/?lang=fr

# 3 IQFA'X Colloquium – Practical Information

## 3.1 Venue

**The colloquium takes place at the CNRS Headquarters, campus Paris Michel-Ange.** The exact address is CNRS - Délégation Paris Michel-Ange, 3 rue Michel-Ange - 75794 Paris cedex 16.

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

## 3.2 Access to the Campus Michel-Ange - CNRS Headquarters

**The CNRS Headquarters main entrance is located close to the Metro station entitled "Michel-Ange Auteuil" of the Line 10**. You can plan your itinerary on the RATP[13] website.

You can join us on the Michel-Ange campus of the CNRS Headquarters using the following means, see also the Local Map on Fig. 1 and the Tramway line on Fig. 2:

- *By public transportation*:
  From the aiport - Take the Orlyval tube up to the RER-B station "Antony", then RER-B up to the station "Denfert-Rochereau", then Metro Line 6 up to the station "La Motte Picquet Grenelle", and then Metro Line 10 up to the station "Michel-Ange Auteuil".
  From the station "Michel-Ange Auteuil" - Just walk 30 m up to the CNRS Headquarters main gate.


Figure 1: Access map to CNRS Headquarters, Michel-Ange campus.

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

## 3.3 Registration & badge

The participants' venue will be made available from Wednesday the $13^{th}$ of November at 8:00 am, in the main building of the Michel-Ange CNRS Campus. Once the building reached and its entrance passed, you'll discover both the Hall and on your right the Amphitheater, where the colloquium takes place.

***Note that, for security reasons, a valid passport or ID card is required to enter the CNRS Headquarters.***

[13] https://www.ratp.fr/
[14] https://iqfacolloq2019.sciencesconf.org/resource/acces
[15] https://www.cnrs.fr/paris-michel-ange/spip.php?article748


Figure 2: Map of the Paris public transportation service. For those who reach Paris via Orly airport, Metro Line 10 serves the CNRS Headquarters campus at the station "Michel-Ange Auteuil". Line 10 connects to Line 6 at the station "La Motte Picquet Grenelle", which itself connects to the REB-B at the station "Denfert-Rochereau". The RER-B then connects to Orly airport via the Orlyval tube at the station "Antony".

### 3.4 Internet Connection

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

### 3.5 Coffee breaks, lunches & buffet

During the colloquium, all coffee breaks and lunches will be taken on site in the adjacent rooms next the the theater. Coffee breaks and lunches are free of charge for all registered participants. The banquet of the colloquium is organized on Thursday the $14^{th}$ of November, and will be taken on site. It will start around 7:00 pm, right after Thursday's poster session (see the program in Sec. 2.2) and is free of charge for people who have mentioned their participation at the early registration stage.

### 3.6 Organization & financial supports

| | |
|---|---|
| *This colloquium is organized by:* | the GDR IQFA, |
| | & the CNRS Institute of Physics (INP), |
| *at* | the CNRS Headquarters, |
| *with the financial supports of:* | the CNRS, through its Institutes INP, INSIS, and INS2I,<br>the DIM Sirteq, https://www.sirteq.org, of the Région Ile de France,<br>Quandela, http://quandela.com,<br>and ID Quantique, https://www.idquantique.com.<br>*that are warmly acknowledged.* |

### 3.7 Local organization committee for IQFA'X - CNRS Headquarters

| | |
|---|---|
| *Presidents:* | Anaïs Dréau, CNRS, Uni. Montpelier & Sébastien Tanzilli, CNRS, Uni. Côte d'Azur; |
| *IQFA CS Members:* | Alexei Ourjoumtsev, CNRS, CdF, Paris & Nicolas Treps, Sorbonne Uni, Paris; |
| *CNRS-INP Members:* | Bettina Saunière, Paris Michel-Ange,<br>Marine Charlet-Lambert, Paris Michel-Ange,<br>Pauline Dubois, Paris Michel-Ange,<br>Chloé Malanda, Paris Michel-Ange,<br>Marie Signoret, Paris Michel-Ange; |
| *With the remote help of:* | Carmen Toderasc (admin.), CNRS, Collège de France, Paris,<br>Nathalie Koulechoff, CNRS, Uni. Côte d'Azur,<br>& Bernard Gay-Para, CNRS, Uni. Côte d'Azur. |

# 4 Abstracts of the contributions

In the following, you can find, after the tutorial lectures, invited talks, and contributed talks, all the poster contributions sorted per ART.
The contributed talks correspond to poster contributions that have been selected by our Scientific Committee for oral presentations, as can be seen in the Program in Sec. 2.2.

# Table of contents

# Tutorial Talks

# Device-independent quantum information processing

Antonio Acín[1*]
[1] *ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain*

Device-independent quantum information processing represents a new framework for quantum information applications in which devices are seen as black boxes processing classical information. In particular, no assumptions are made on the inner working of these devices except their quantum functioning. The talk introduces the main ideas and tools of the device-independent scenario and argues why it is especially relevant for quantum cryptography applications.

* antonio.acin@icfo.eu

# Quantum acoustics experiments

Andreas Wallucks[1], Igor Marinković[1], Bas Hensen[1], Robert Stockill[1], Moritz Forsch[1], and Simon Groeblacher[1]*
[1]*Kavli Institute of Nanoscience, Department of Quantum Nanoscience,*
*Delft University of Technology, 2628CJ Delft, The Netherlands*

Mechanical systems have recently attracted significant attention for their potential use in quantum information processing tasks, for example, as compact quantum memories or as transducers between different types of quantum systems. Early experiments included ground-state cooling of the mechanical motion and squeezing of the optical field. Recent advances have allowed to perform measurements which realize various mechanical quantum states.

Here, we would like to discuss several experiments where we demonstrate non-classical behavior of mechanical motion by coupling a micro-fabricated acoustic resonator to single optical photons. Our approach is based on optomechanical crystals, which possess engineered mechanical resonances in the Gigahertz regime that can be addressed optically from the conventional telecom band. Our measurements establish quantum control over acoustic motion, including the heralded generation and on-demand readout of single phononic excitations. We further demonstrate high quality light-matter entanglement as well as heralded entanglement between two mechanical modes employing quantum optics protocols. These results are a promising step towards using such devices for quantum information processing tasks and testing quantum physics with massive objects.

* s.groeblacher@tudelft.nl

# Quantum error correction in ion traps

Jonathan Home[1*]
[1] *Trapped-ion Quantum Information, Institute for Quantum Electronics, ETH Zürich, Otto-Stern Weg 1, Switzerland*

Quantum error-correction is expected to consume a large fraction of the resources of any future quantum computer. I will describe simple manifestations of quantum error correction using both the motional and internal degrees of freedom of trapped atomic ions. Trapped ions offer high fidelity quantum state control. For the internal states, error-correcting codes have been reslized using multiple ions. After describing the basic toolbox, I will describe how we were recently able to also extend this basic control to the repeated readout and stabilization, as is required for long-term error-correction [1]. In an alternative line of research, I will also describe how we have used trapped-ion motion to encode a logical qubit in an error-correcting code which corrects for continuous variable errors [2]. I will present prospects for scaling these systems to the large scales required for effective error correction suitable for quantum computing.

[1] V. Negnevitsky, M. Marinelli et al. Nature 563, 527-531 (2018)
[2] C. Flühmann et al. Nature 566, pp. 513-517 (2019)

* jhome@phys.ethz.ch

# Quantum algorithms : an overview

Ashley Montanaro[1]*
[1]*School of Mathematics, University of Bristol, Bristol, UK*

Quantum computers are designed to outperform their classical counterparts by running quantum algorithms. Some quantum algorithms achieve exponential speedups over the best classical algorithms known, while others achieve more modest polynomial speedups, but have broad applications. Far from the popular misconception that only a few quantum algorithms are known, there are many examples ; indeed, the Quantum Algorithm Zoo website currently lists 404 papers on quantum algorithms. In this talk, I will give an overview of a few prominent quantum algorithms that have been developed, together with their applications. These include algorithms for cryptography ; combinatorial search and optimisation ; and simulation of quantum-mechanical systems. The talk will not assume any prior knowledge of quantum algorithms or the theory of quantum computing. A reference is [1], although the talk will also cover more recent results.

[1] Quantum algorithms : an overview. A. Montanaro. *npj Quantum Information* vol. 2, 15023, 2016 ; arXiv :1511.04206

* ashley.montanaro@bristol.ac.uk

# Trapped ions for quantum networks

Tracy E. Northup[1]*
[1]*Institute for Experimental Physics, University of Innsbruck, Technikerstraße 25/4, Innsbruck, Austria*

Future quantum networks offer a route to quantum-secure communication, distributed quantum computing, and quantum-enhanced sensing. The applications of a given network will depend on the capabilities available at its nodes, which may be as simple as quantum-state generation and measurement or as advanced as universal quantum computing [1]. In this tutorial, we will focus on quantum nodes based on trapped ions, an experimental platform with which high-fidelity state preparation, gate operations, and readout have been demonstrated. We will examine how coherent interfaces can be constructed at quantum nodes between single ions and single photons, either via free-space light collection or via coupling trapped ions to the mode of an optical resonator [2, 3]. Surveying the state of the art concerning the transfer of quantum states between remote trapped-ion systems, we will highlight the central challenges faced by current experiments.

[1] S. Wehner, D. Elkouss, R. Hanson, "Quantum internet : A vision for the road ahead," Science **362**, 303 (2018).
[2] H. J. Kimble, "The quantum internet," Nature **453**, 1023 (2008).
[3] T. E. Northup and R. Blatt, "Quantum information transfer using photons," Nat. Photonics **8**, 356 (2014).

* tracy.northup@uibk.ac.at

## Quantum-safe cryptography, from research to industry

Grégoire Ribordy[1]*
[1] *Id Quantique SA, Geneva, Switzerland*

Recent advances in the field of quantum computing make it important for government and organizations to make plans toward quantum-safe cryptography. Quantum key distribution is one of the two approaches to achieve long-term security, in the quantum era. Market demand for this technology is increasing and large scale initiatives, for example in China or Europe, indicate that Quantum Key Distribution will play an important role in future-proofing critical infrastructure. In this presentation, we will present the current performance of commercial quantum key distribution systems, we will discuss popular use cases and we will review market trends that sustain adoption of this technology.

* gregoire.ribordy@idquantique.com

# Pure quantum light generation in the solid-state

Pascale Senellart*
*Centre de Nanosciences et Nanotechnologies, CNRS, Université Paris Saclay, 10 Boulevard Thomas Gobert, 91120 Palaiseau, France*

The ability to generate light in pure quantum states is central to the development of quantum-enhanced technologies. Recently, artificial atoms in the form of semiconductor quantum dots have emerged as an excellent platform for quantum light generation [1, 2]. By placing the quantum dot in an optical microcavity, pure dephasing phenomena are strongly suppressed [3] and single photon wavepackets with very high quantum purity in the frequency domain are generated. This is demonstrated at unprecedented high efficiency that allows scaling up linear quantum optical technologies [4]. The system is also shown to generate light pulses in a pure quantum superposition in the photon number basis, a feature that has never been demonstrated even with natural atoms. This is obtained through coherent control of the artificial atom transition : a pure quantum superposition of vacuum and one-photon is generated with a full control of their relative populations. Driving the system even stronger, a coherent superposition of vacuum, one- and two-photons is generated—a state that shows phase super-resolving interferometry [5].

[1] N. Somaschi, et al. Nature Photonics, 10, 340 (2016)
[2] P Senellart, G Solomon, A White, Nature Nanotechnology 12 (11), (2017)
[3] T. Grange et al., Physical Review Letters 118, 253602 (2017)
[4] C Antón, et al., arXiv :1905.00936, Optica 2019 in Press
[5] J. C. Loredo, C. Antón, et. al, arXiv :1810.05170, Nature Photonics 2019

* pascale.senellart-mardon@c2n.upsaclay.fr

# Invited Talks

# 2D material enabled Quantum networks

Dmitri Efetov[1 *]

[1] *ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain*

Integrated quantum networks IQNs will allow quantum processors, quantum repeaters, as well as quantum sensing and metrology systems that use entanglement and squeezing to surpass classical devices, however IQNs require the scalable integration of a variety of dedicated quantum devices, which to this day remains impossible. It was recently shown that due to the elastic and flexible mechanical properties of 2D materials, these can be effortlessly deposited onto photonic circuit platforms, such as Si, SiN and CMOS, in a scalable, non-invasive and mutually compatible way. As 2D materials can be atomically engineered into vertical hetero-structures, it is possible to combine and hybridize the functionalities of the different materials to engineer band-gaps, emission spectra and generate enhanced quantum effects. The breakthrough will be the development and prototyping of a full set of on-chip quantum components and the scalable integration of these into prototype chip-based IQNs.

* dmitri.efetov@icfo.eu

# Quantum-enhanced sensing using non-classical spin states of a highly magnetic atom

Sylvain Nascimbene*
*Laboratoire Kastler Brossel, CNRS, Collège de France, Ecole Normale Supérieure, Sorbonne Université, 11 place Marcelin Berthelot, 75005 Paris*

The precision of a quantum sensor can overcome its classical counterpart when its constituents are entangled. We present the experimental realization of highly sensitive quantum states of the electronic spin of Dysprosium $J = 8$ [1, 2]. We generate these states using an off-resonant laser beam close to the intercombination line, simulating the one-axis twisting Hamiltonian.

Starting in a coherent spin state, the non-linear spin dynamics leads to gaussian squeezed states, complex non-gaussian states [2], and 'kitten' states (superposition of coherent spin states with opposite magnetizations) [1]. We show that, for non-gaussian spin states, single magnetic sublevel resolution is required to reach optimal measurement sensitivity.

We also study the ground state of the electronic spin in the presence of the non-linear spin coupling, which simulates an Ising model of $2J = 16$ spins 1/2 interacting at infinite range [3]. We reveal a crossover between paramagnetic and ferromagnetic behaviors, separated by a quantum critical region where we find non-classical spin correlations.

[1] T. Chalopin, C. Bouazza, A. Evrard, V. Makhalov, D. Dreon, J. Dalibard, L.A. Sidorenkov, S. Nascimbene, Quantum-enhanced sensing using non-classical spin states of a highly magnetic atom, Nat. Commun. **9**, 4955 (2018)
[2] A. Evrard, V. Makhalov, T. Chalopin, L.A. Sidorenkov, J. Dalibard, R. Lopes, S. Nascimbene, Enhanced magnetic sensitivity with non-gaussian quantum fluctuations, Phys. Rev. Lett. **122**, 173601 (2019)
[3] V. Makhalov, T. Satoor, A. Evrard, T. Chalopin, R. Lopes, S. Nascimbene, Probing quantum criticality and symmetry breaking at the microscopic level, Phys. Rev. Lett. **123**, 120601 (2019)

* sylvain.nascimbene@lkb.ens.fr

# Continuous Variables Quantum Complex networks

Valentina Parigi*
*Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-PSL Research University,*
*Collège de France ; 4 Place Jussieu, 75252 Paris, France*

In the last twenty years network theory has provided a deep insight of complex systems, assembling theoretical tools able to the describe dynamical behavior of biological, social and technological structures. Fundamental constituents of matter, such as photons, electrons and atoms, are quantum objects. However, when we want to account for the emergence of the classical world from its microscopic quantum constituents, or to exploit quantum properties in useful tasks we need to adequately describe- in the first case- and to control - in the second case- a large number of quantum objects and their non-trivial interactions. Multimode quantum optical systems are a natural testbed for exploring complex network structures in a quantum scenario. Indeed, optical parametric processes pumped by frequency combs generate multimode quantum states of light where the structure of quantum correlations can be easily shaped [1]. I will review the experimental platforms, I will describe how they can be used to simulate complex quantum environment, I will show the interest of complex quantum graphs in quantum communication protocols, and how complex network theory can be used to classify non-trivial non-Gaussian quantum states[2, 3].

[1] Y. Cai, J. Roslund, G. Ferrini, F. Arzani, X. Xu, C Fabre and N. Treps, Nature Communications **8**, 15645 (2017)
[2] J. Nokkala, F. Arzani, F. Galve, R. Zambrini, S. Maniscalco, J. Piilo, N. Treps and V. Parigi, New Journal of Physics **20**, 053024 (2018).
[3] M. Walschaers, S. Sarkar, V. Parigi, and N. Treps, Phys. Rev. Lett. **121**, 220501(2018)

* valentina.parigi@lkb.upmc.fr

# Contributed Talks

# Photon Bunching in a Rotating Reference Frame

Sara Restuccia[†,1], Marko Toroš[†,2,3], Graham M. Gibson[1], Hendrik Ulbricht[2], Daniele Faccio[1] and Miles J. Padgett[1*]
[1]*School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, UK*
[2]*Department of Physics and Astronomy, University of Southampton, SO17 1BJ, UK*
[3]*Department of Physics and Astronomy, University College London, London WC1E 6BT, United Kingdom*

The unification of quantum mechanics and general relativity into a single consistent theory is one of modern physics open dilemmas. Traditionally, this problem has been approached by proposing theories that quantised gravity while retaining the foundational principles of quantum mechanics [1]. While an abundance of quantum gravity theories have now been proposed (string theory being one such example), exploring these theories experimentally has been a significant challenge. In particular, in conventional quantum gravity theories general relativistic effects are predicted to occur at the Plank scale which is tens of orders of magnitude away from current measurement sensitivities. The lack of experimental confirmation for any particular quantum gravity theory has lead to a recent theoretical shift in the way the unification of these two theories is tackled. In particular, an alternative approach has been suggested where the need to quantise gravity is called into question, but instead suggests that a unified theory should require the current framework of quantum theory to be modified i.e. suggesting that the unified theory be a "gravitize quantum theory" [1]. It is therefore of key importance that we identify any experimental approach that can provide evidence of the quantisation of gravity or spacetime. No theory can provide such evidence or even predict beforehand the outcome of such tests without making explicit assumptions on the quantisation, or not, of spacetime. Experiment alone can provide the required evidence and guide future research in the field.

In the paper "Photon Bunching in a Rotating Reference Frame" [2], we carried out an experiment that tested the role of relativity in quantum mechanics. In particular the experiment probed the behaviour of entangled photons in a noninertial reference frame. This was done through the use of a "quantum gyroscope" composed of a Hong-Ou-Mandel (HOM) interferometer on a rotating table [3]. The Hong-Ou-Mandel effect is a nonclassical phenomenon in which two indistinguishable photons, when interfered at a beam splitter combine by bunching together, thus always exiting the beam splitter in pairs. It is important to notice the similarity of the HOM set up with a Sagnac interferometer where two counter-propagating waves create an interference pattern at a common beam splitter. It is well known that the rotation of a Sagnac interferometer results in a phase shift in the interference and this effect is the basis of an optical gyroscope. In our experiment we therefore studied the effect of this uniform rotation on the distinguishability of the photons. We were therefore able to measure a shift in position of the HOM dip as a function of the rotation speed of the table. This relative delay in the photons arrival is equivalent to the classical Sagnac effect with the sole difference being that while in the classical set-up the rotation motion induces a change in the interference of the two beams, in the quantum set-up the change is in the quantum interference of the two photons. This experiment therefore implies that the quantum interference of two photons is affected by non-inertial motion, which opens new pathways to probe the relation between gravity and quantum mechanics.

[1] R. Howl, R. Penrose and I. Fuentes, "Exploring the unification of quantum theory and general relativity with a Bose-Einstein condensate", New J. Phys. **21**, 043047 (2019).
[2] S. Restuccia, M. Toroš, G.-M. Gibson, H. Ulbricht, D. Faccio and M.-J. Padgett, "Photon Bunching in a Rotating Reference Frame", Phys. Rev. Lett. **123**, 110401 (2019).
[3] C.-K. Hong, Z.-Y. Ou, and L. Mandel, "Measurement of Subpicosecond Time Intervals between Two Photons by Interference", Phys. Rev. Lett. 59, 2044 (1987).

* s.restuccia.1@research.gla.ac.uk
[†]These authors contributed equally.

# High-sensitivity inertial measurements by cold-atom interferometry

Remi Geiger[1]* and Romain Gautier[1], Matteo Altorio[1], Leonid Sidorenkov[1], Arnaud Landragin[1]
[1]*LNE-SYRTE, Observatoire de Paris, Université PSL, CNRS,*
*Sorbonne Université, 61 avenue de l'Observatoire, 75014 Paris, France*

Cold-atom inertial sensors target several applications in navigation, geoscience and tests of fundamental physics. Reaching high sampling rates and high inertial sensitivities, obtained with long interrogation times, represents a challenge for these applications. We report on the interleaved operation of a cold-atom gyroscope, where 3 atomic clouds are interrogated simultaneously in an atom interferometer featuring a 3.75 Hz sampling rate and an interrogation time of 801 ms. Interleaving improves the inertial sensitivity by efficiently averaging vibration noise, and allows us to perform dynamic rotation measurements in a so-far unexplored range. We demonstrate a stability of $3 \times 10^{-10}$ rad.s$^{-1}$, which competes with the best stability levels obtained with fiber-optics gyroscopes. Our work validates interleaving as a key concept for future atom-interferometry sensors probing time-varying signals, as in on-board navigation and gravity-gradiometry, searches for dark matter, or gravitational wave detection [1].

[1] D. Savoie, M. Altorio, B. Fang, L. A. Sidorenkov, R. Geiger and A. Landragin, "Interleaved atom interferometry for high-sensitivity inertial measurements", Science Advances Vol. 4, no. 12, eaau7948 (2018).

* remi.geiger@obspm.fr

# Quantum microwaves with a dc-biased Josephson junction

Ambroise Peugeot, Gerbold Ménard, Iouri Moukharski, Carles Altimiras,
Denis Vion, Philippe Joyez, Patrice Roche, Daniel Esteve and Fabien Portier*
*SPEC, CEA, CNRS, Université Paris-Saclay, CEA-Saclay, 91191 Gif-sur-Yvette Cedex, France*

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

[1] M. Hofheinz et al., Phys. Rev. Lett. **106**, 217005 (2011)
[2] C. Rolland et al., Phys. Rev. Lett. **122**, 186804 (2019)
[3] M. Westig et al., Phys. Rev. Lett. **119**, 137001 (2017)

* fabien.portier@cea.fr

# Quantum Protocol Zoo

Harold Ollivier[1], Rhea Parekh[1,3], Shraddha Singh[1], Natansh Mathur[1,4], Mina Doosti[2], Gözde Ustün[1], Bas Dirkse[5,6,7], Victoria Lipinska[5,6], Jérémy Ribeiro[5,6], Mahshid Delavar[2], Niraj Kumar[2], Gláucia Murta[5,6], Atul Mantri[2], Celine Chevalier[8], Marc Kaplan[9], Elham Kashefi[2,9,1,*]

[1]*LIP6, CNRS, Sorbonne Université, France*
[2]*School of Informatics, University of Edinburgh, UK*
[3]*Department of Physics, Indian Institute of Technology, Roorkee, India,*
[4]*Department of Computer Science and Engineering, Indian Institute of Technology, Roorkee, India,*
[5]*QuTech, Delft University of Technology, Netherlands,*
[6]*Kavli Institute of Nanoscience, Delft University of Technology, Netherlands,*
[7]*QuSoft, CWI and University of Amsterdam, Netherlands,*
[8]*CRED, Universite Pantheon-Assas, Paris II, France,*
[9]*VeriQloud, France*

We introduce a framework for presenting quantum communication protocols to make them readily available for a broad range of communities interested in the use cases of quantum technology. The framework describes the overall functionality of a set of protocols and presents them compactly and consistently while also decomposing them into general sub-routines. This decomposition is grounded in cryptographic frameworks – especially abstract cryptography [1] – as it provides sound guidelines for defining elementary resources and using them to build more advanced ones.

The Quantum Protocol Zoo repository is hosted at *https://wiki.veriqloud.fr*. The *Protocol Library* covers families of quantum network protocols classified according to the advanced stages of a quantum internet [2]; and the *Certification Library* presents different certification and benchmarking techniques and protocols for quantum devices. For each protocol, we provide its detailed outline, assumptions, resources and requirements, procedure description and properties. Following this format, several concrete protocols have already been added, and we are also developing an *open-source library* where the protocols have been implemented on a simulation platform *SimulaQron* [3]. Furthermore, we have developed a novel concept of resource visualisation for quantum communication protocols. This includes two user-friendly interfaces : *Protocol decomposition*, to identify the types of resources required for each protocol; and *Knowledge Graph*, an interactive interface connecting all the listed protocols with their required resources in a single graph.

We also revisit network layering for quantum internet protocols. As protocols are decomposed into more elementary functions and are simulated, we get a precise view of service requirements every protocols has with respect to various network layers on top of which they are build. This top-down approach complements the one promoted by other members of the *Quantum Internet Alliance* and is emphasizing the importance of identifying elementary functions that might be composable and proving such composability. This work has started with the definition of a quantum link resource providing a heralded and flow-controlled qubit sending service. The elementary function will be integrated into a dedicated library enhancing the network simulation platform.

We aim at continuing this work by integrating additional quantum internet and certification protocols, to make the protocol zoo a valuable resource for developing and realising real-world use-cases, applications, future networks and quantum devices. By providing code examples and utility functions we lower the bar for building proof of concepts simulations and experiments, while also contributing to setting up a standard model of a secure and robust network stack. We invite everyone from the quantum information science community to join and contribute to this initiative by submitting protocols to the zoo and using it to identify potential applications and proof of concepts experiments.

[1] M Ueli and R Renner, Abstract Cryptography, IN INNOVATIONS IN COMPUTER SCIENCE (2011)
[2] S Wehner, D Elkouss, and R Hanson, Quantum internet : A vision for the road ahead, Science **362**, eaam9288 (2018)
[3] A Dahlberg and S Wehner, Simulaqron—a simulator for developing quantum internet software, Quantum Science and Technology **4**, 015001 (2018)

* quantumprotocolzoo@gmail.com

# Transform-limited photons from a long-lived tin-vacancy spin in diamond

Matthew Trusheim*,[1], **Benjamin Pingault***,[2,3*] and Noel Wan[1], Mustafa Gündoğan[2], Lorenzo De Santis[1], Romain Debroux[2], Dorian Gangloff[2], Kevin Chen[1], Michael Walsh[1], Joshua J. Rose[2], Jonas N. Becker[4], Benjamin Lienhard[1], Eric Bersin[1], Dominika Lyzwa[1], Girish Malladi[5], Hassaram Bakhru[5], Ian Walmsley[4], Mete Atatüre[2], and Dirk R. Englund[1]

[1]*Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

[2]*Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom*

[3]*John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA*

[4]*Clarendon Laboratory, University of Oxford, Parks road, Oxford, OX1 3PU, United Kingdom*

[5]*College of Nanoscale Science and Engineering, Suny Poly, 257 Fuller Road, Albany, NY 12203, United States*

Solid-state quantum emitters that couple coherent optical transitions to long-lived spin states are essential for quantum networks. In particular, group IV colour centres in diamond, such as the silicon-vacancy (SiV) and the germanium-vacancy (GeV) centres, have attracted attention due to their excellent optical properties in nanostructures [1] and optically accessible spin [2**?** ]. However, their spin coherence is limited by phonon-induced transitions within their ground state manyfold and it is thus necessary to cool down the SiV centre to millikelvin temperatures. [4] or submit it to large crystal strain [5] to to eliminate this source of decoherence.

Here we report on the spin and optical properties of a recently discovered group IV colour centre : the tin-vacancy (SnV) centre in diamond [6]. Through magneto-optical spectroscopy of single centres at 4 K, we first verify the inversion-symmetric electronic structure of the SnV, similar to that of the SiV. Using photoluminescence excitation, we show that optical transition linewidths are lifetime-limited, even in nanostructures, showing evidence of the excellent optical properties of the SnV. We then initialise and read out the spin state of single centres and show that the spin lifetime is longer than for SiV and GeV centres under similar conditions. The spin dephasing time, evaluated through optically detected magnetic resonance, is consistent with expected phonon-induced decoherence, similar to that of SiV at 4 K. However, cooling SnV down to 2 K is expected to provide the same spin coherence enhancement as for SiV at millikelvin temperatures, thus alleviating the need for dilution fridges. These results indicate that the SnV combines excellent optical properties with superior spin properties compared with the SiV and GeV centres. It is thus a promising candidate as a spin-photon interface for quantum networking applications.

[1] A. Sipahigil*, R. Evans*, D. Sukachev*, M. Burek, J. Borregaard, M. Bhaskar, C. Nguyen, J. Pacheco, H. Atikian, C. Meuwly, R. Camacho, F. Jelezko, E. Bielejec, H. Park, M. Lončar, and M. Lukin, "An integrated diamond nanophotonics platform for quantum-optical networks", Science **354**, 847-850 (2016).

[2] B. Pingault*, J. Becker*, C. Schulte, C. Arend, C. Hepp, T. Godde, A. Tartakovskii, M. Markham, C. Becher, and M. Atatüre, "All-optical formation of coherent dark states of silicon-vacancy spins in diamond", Phys. Rev. Lett. **113**, 263601 (2014).

[3] B. Pingault, D. Jarausch, C. Hepp, L. Klintberg, J. Becker, M. Markham, C. Becher, and M. Atatüre, "Coherent control of the silicon-vacancy spin in diamond", Nat. Commun. **8**, 15579 (2017).

[4] D. Sukachev*, A. Sipahigil*, C. Nguyen*, M. Bhaskar, R. Evans, F. Jelezko, and M. Lukin, "Silicon-vacancy spin qubit in diamond : a quantum memory exceeding 10 ms with single-shot state readout", Phys. Rev. Lett. **119**, 223602 (2017).

[5] Y. Sohn*, S. Meesala*, B. Pingault*, H. Atikian, J. Holzgrafe, M. Gündoğan, C. Stavrakas, M. Stanley, A. Sipahigil, J. Choi, M. Zhang, J. Pacheco, J. Abraham, E. Bielejec, M. Lukin, M. Atatüre, and M. Lončar, "Controlling the coherence of a diamond spin qubit through its strain environment", Nat. Commun. **9**, 2012 (2018).

[6] M. Trusheim*, B. Pingault*, N. Wan, M. Gündoğan, L. De Santis, K. Chen, M. Walsh, J. Rose, J. Becker, B. Lienhard, E. Bersin, D. Lyzwa, G. Malladi, H. Bakhru, I. Walmsley, M. Atatüre, and D. Englund, "Transform-limited photons from a tin-vacancy spin in diamond", Arxiv 1811.07777 (2018).

* bpingault@seas.harvard.edu

## A fully stabilised logical quantum bit encoded in grid states of a superconducting cavity

P. Campagne-Ibarcq[1,2], A. Eickbusch[2], S. Touzard,[1] E. Zalys-Geller,[1] N.E. Frattini,[1] V.V. Sivak,[1] P. Reinhold,[1] S. Puri,[1] S. Shankar,[1] R.J. Schoelkopf,[1] L. Frunzio,[1] M. Mirrahimi,[2] M.H. Devoret[1*]
[1]*Department of Applied Physics, Yale University, New Haven, CT 06520, USA*
[2] *Quantic Team, Inria Paris, 2 rue Simone Iff, 75012 Paris, France*

The realization of universal quantum computation is currently hindered by noise that modifies the state of physical qubits, causing logical errors. Fortunately, such errors can be detected and corrected if quantum information is encoded non-locally. Applying this idea to hardware efficient bosonic codes, Gottesman Kitaev and Preskill proposed to encode a protected qubit non-locally in the phase-space of a harmonic oscillator. Here, we prepare and stabilize such a qubit using repeated applications of a novel protocol on a superconducting microwave cavity. We demonstrate significant suppression of all logical errors, in quantitative agreement with a theoretical estimate based on the measured imperfections of the experiment. The developed techniques are applicable to other continuous variable systems and, in contrast with previous implementations of quantum error correction, can mitigate the impact of a wide variety of noise processes. Our results pave the way towards fault-tolerant quantum computation with bosonic modes.

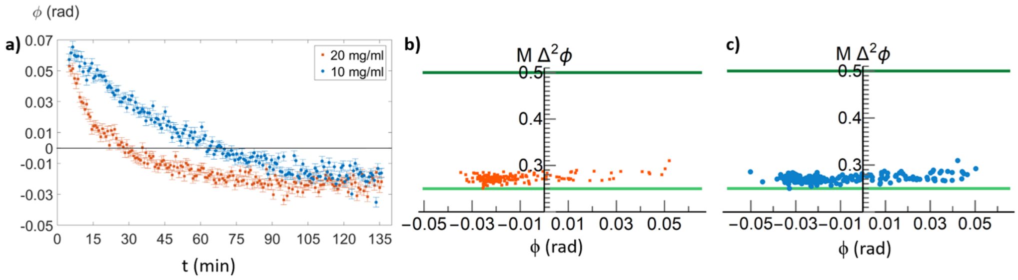
[*] philippe.campagne-ibarcq@inria.fr

Tracking enzymatic activity with quantum light

Valeria Cimini[1], Marta Mellini[1], Giordano Ramponi[1], Marco Sbroscia[1], Livia Leoni[1], Marco Barbieri[1,2] and Ilaria Gianani[1,3]
[1]*Dipartimento di Scienze, Universitá degli Studi Roma Tre, Via della Vasca Navale 84, 00146, Rome, Italy*
[2]*Istituto Nazionale di Ottica - CNR, Largo Enrico Fermi 6, 50125, Florence, Italy*
[3]*Dipartimento di Fisica, Sapienza Universitá di Roma, P.le Aldo Moro, 5, 00185, Rome, Italy*

One of the most sought application of Quantum Metrology is the implementation of quantum biosensors. The reason behind this is the need of non-invasive probes that may damage or alter the activity of the biological specimen. It is then necessary to look at a trade-off between the amount of modification and the quality of the measurement. The origin and details of the bound on the uncertainty are captured by inspecting the behavior of light at the quantum level. Quantum metrology is the art of identifying how quantum properties need being controlled and measured, and provides clear guidelines on preparing the best possible probe for a given intensity. Using quantum light superior precision is possible [1]. We applied methods of quantum metrology, using single photon N00N states, to monitor the activity of an enzymatic reaction that leads to a change in optical activity of the products with respect to that of the substrate material. We have employed this technique with a well known biochemistry reaction i.e. the hydrolysis of sucrose enabled by invertase. In this reaction, sucrose, a right-handed optically active molecule, is hydrolyzed into fructose and glucose, whose mixture has a left-handed activity.

Quantum light probes are generated by means of two-photon quantum interference, starting with a pair of photons in orthogonal linear polarizations. Since the photons are indistinguishable, in the circular polarizations the behavior is that of a quantum superposition of the two photons being both in the same polarization state. By passing through the sample, the photon pair accumulates an optical phase $\phi$, as a consequence of optical activity. This occurs twice as fast as for classical light, hence ensuring superior accuracy [2]. We measure in real time the change of optical activity of a sucrose solution (Fig. a) after adding invertase to the sample. We record the kinetics at room temperature with two different invertase concentrations, 10 mg/ml and 20 mg/ml at a sampling rate of $37s$. For each point, the choice of the measurement is optimized with an adaptive scheme to ensure each phase is estimated close to the ultimate precision (Fig. b-c). In conclusion we also investigated possible effect of laser light on invertase activity, additional reactions were carried out with invertase samples illuminated for $1h$ with laser at different frequencies and intensities. Comparison to untreated (i.e. not illuminated) invertase revealed that light exposure is detrimental to enzymatic activity, supporting the development of the quantum metrology approach for non-invasive measurements.




[1] V. Giovannetti, S. Lloyd, and L. Maccone, *Quantum-enhanced measurements : beating the standard quantum limit*, Science **306**, 1330-1336 (2004).
[2] E. Roccia, V. Cimini, M. Sbroscia, I. Gianani, L. Ruggiero, L. Mancino, M.G. Genoni, M.A. Ricci, and M. Barbieri, *Multiparameter approach to quantum phase estimation with limited visibility*, Optica **5** N. 10, 1171-1176 (2018).

# Self-testing - a trustworthy certification tool for quantum communications

Jean-Daniel Bancal[1,2], Davide Orsucci[1], Enky Oudot[1,2], Pavel Sekatski[1], Xavier Valcarce[1], Sebastian Wagner[1], and Nicolas Sangouard[1]

[1]*Departement Physik, Universität Basel, Klingelbergstraße 82, 4056 Basel, Schweiz* [2]*Département de Physique Appliquée, Université de Genève, 1211 Genève, Suisse*

A quantum state can be characterized from the violation of a Bell inequality. In this case, the certification holds without assumption about the internal working of devices used in the Bell test. This is known as self-testing [1]. The aim of this contribution is to show that self-testing can be used as a trustworthly certification tool which could play a central role in future quantum communication protocols.

We will introduce self-testing through the simplest and most common Bell inequality, the Clauser-Horne-Shimony-Holt (CHSH) inequality. The sole knowledge of the CHSH score is known to be sufficient to characterize the singlet state even in noisy scenario. However, the mininum CHSH violation leading to a non-trivial self-testing bound is an open question. We will give an example showing that the CHSH self-testing threshold is quite far from the local bound [2]. We will then introduce new tools to account for finite statistics in CHSH based self-testing. Applying these tools to data from the loophole-free Bell experiment [W. Rosenfeld et al. Phys. Rev. Lett. 119, 010402 (2017)], we will show that self-testing can be used in an elementary link of a quantum network to certify the successful distribution of a Bell state over 398 meters [3].

We will then show how self-testing can be used to certify quantum channels with classical and/or quantum outputs. This includes quantum units to store (quantum memories), process (frequency converters, logical gates) and to measure (quantum instruments) quantum information [4–6]. The proposed certifications are resistant to noise and could soon certify experimental realisations.

Finally, we will introduce connections between self-testing and quantum information applications. For exemple, we will show that self-testing can certify that a given setup can be used for quantum key distribution where the security guarantees hold independently of the details of the actual implementation.

[1] D. Mayers and A. Yao, "Self testing quantum apparatus," Quantum Info. Comput., 4 :273, 2004. arXiv :0307205.

[2] X. Valcarce, P. Sekatski, D. Orsucci, E. Oudot, J.-D. Bancal and N. Sangouard, "What is the minimum CHSH score certifying that a state contains the singlet ?," arXiv :1910.04606

[3] J.-D. Bancal, K. Redeker, P. Sekatski. W. Rosenfeld and N. Sangouard, "Device-independent certification of an elementary quantum network link," arXiv :1812.09117

[4] P. Sekatski, J.-D. Bancal, S. Wagner, and N. Sangouard, "Certifying the Building Blocks of Quantum Computers from Bell's Theorem," Phys. Rev. Lett. 121, 180505 (2018)

[5] J.-D. Bancal, N. Sangouard and P. Sekatski "Noise resistant device-independent certiication of Bell state measurements," Phys. Rev. Lett. 121, 25056 (2018)

[6] S. Wagner, J.-D. Bancal, N. Sangouard and P. Sekatski "Device-independent charaterization of quantum instruments," arXiv :1812.02628

# Chip-based daylight quantum-key-distribution at 1550 nm

M. Avesani[1], L. Calderaro[1], M. Schiavon[1,2], A. Stanco[1], C. Agnesi[1], A. Santamato[1], M. Zahidy[1], A. Scriminich[1], G. Foletto[1], G. Contestabile[3], M. Chiesa[4], D. Rotta[4], M. Artiglia[5], A. Montanaro[5], V. Sorianello[5], F. Vedovato[1], G. Vallone[1,6] and P. Villoresi[1]*

[1]*Dipartimento di Ingegneria dell'Informazione, Università di Padova, via Gradenigo 6B, 35131 Padova, Italy*
[2]*Sorbonne Université, CNRS, LIP6, F-75004 Paris, France*
[3]*Istituto TeCIP - Scuola Superiore Sant'Anna, Pisa, Italy*
[4]*InPhoTec, Integrated Photonic Technologies Foundation, Pisa, Italy*
[5]*PNTLab - Consorzio Nazionale Interuniversitario per le Telecomunicazioni, Pisa, Italy*
[6]*Dipartimento di Fisica e Astronomia, Università di Padova, via Marzolo 8, 35131 Padova, Italy*

Among the many quantum protocols [1], Quantum Key Distribution (QKD) [2], allowing two parties to share a cryptographic key with unconditional security, is the most advanced one. Fiber-based QKD technology has already reached the commercial stage, but the high losses in optical fibers limit its maximum operating distance to a few hundred kilometers. This makes satellite technologies fundamental for extending QKD to a continental level. Some key requirements for these technologies are i) full-day functionality, ii) compatibility with standard fiber-based technology at telecom wavelength and iii) a stable free-space optical link. The use of a signal in the telecom C-band (around $1550\,\mathrm{nm}$) gives access to both commercial fiber-based and integrated silicon technologies, that allow to build fast, compact and low-power consuming devices, suitable for future deployment in satellite missions. Moreover, the use of a single-mode fiber (SMF) receiver allows the use of commercially available superconducting nanowire single-photon detectors (SNSPDs), with efficiency up to $90\%$ [4]. The combination of good atmospheric transmission and low solar background noise at this wavelength, together with the spatial filtering provided by the SMF, makes this a suitable solution for daylight transmission. The requirement of a stable link, however, makes it necessary to actively compensate for turbulence induced optical aberration.

In this work, we will describe the QKD system called *QCoSOne* ("Quantum Communication for Space-One"), funded by the Italian Space Agency (ASI), which has been exploited to realise daylight free-space QKD at $1550\,\mathrm{nm}$ in an urban environment [3]. The core of the system is the state encoder, which exploits silicon photonics to integrate decoy- and polarization-modulation on a single chip, allowing to generate, with high stability, the states required by the 3-state 1-decoy QKD protocol described in [5]. At the detection stage, we employed spatial (SMF), spectral ($\lesssim 1\,\mathrm{nm}$) and temporal ($1\,\mathrm{ns}$-wide detection window) filtering to reduce the background noise to less than $400\,\mathrm{Hz}$ during the whole day. To have a stable optical link, we built a position-acquisition and tracking (PAT) system that exploits a beacon at $1064\,\mathrm{nm}$, co-propagating with the quantum signal, and a feedback system at the receiver to correct the turbulence-induced tip-tilt fluctuations of the wavefront.

With this system, we managed to perform multiple QKD runs on a $145\,\mathrm{m}$ channel in the urban area of Padova during the month of April 2019, on several days of clear sky condition. The channel was characterized by around $24\,\mathrm{dB}$ of total losses, on average, and a Fried coherence length of $10$ to $40\,\mathrm{cm}$, corresponding to average to good seeing conditions for astronomical observatory sites. We obtained a sifted key rate ranging from $50$ to $150\,\mathrm{kbps}$, with a measured QBER lower than $0.75\%$ during all the acquisition. By performing classical post-processing, we could get a secure key rate of up to $65.8\,\mathrm{kbps}$, by taking into account finite-size effects.

[1] `https://wiki.veriqloud.fr/index.php\?title=Protocol\_Library`, *retrieved on 09/10/2019*.
[2] V. Scarani *et al.*, "The security of practical quantum key distribution", Rev. Mod. Phys. **81**, 1301 (2009).
[3] M. Avesani *et al.*, "Full daylight quantum-key-distribution at 1550 nm enhabled by integrated silicon photonics", arXiv:1907.10039 (2019).
[4] `https://www.idquantique.com/single-photon-systems/products/id281/`, *retrieved on 09/10/2019*.
[5] D. Rusca *et al.*, "Finite-key analysis for the 1-decoy state QKD protocol", Appl. Phys. Lett. **122**, 171104 (2018).

* matteo.schiavon@lip6.fr

# Remote spin entanglement in semiconductor quantum circuits

Baptiste Jadot,[1] Pierre-André Mortemousque,[1] Emmanuel Chanrion,[1] Vivien Thiney,[1] Arne Ludwig,[2] Andreas D. Wieck,[2] Matias Urdampilleta,[1] Christopher Bäuerle,[1] and Tristan Meunier[1]

[1]*Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, Grenoble, France*

[2]*Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum, Bochum, Germany*

Sharing entanglement at distance on a chip offers a viable route for scalability in quantum circuits. Added up to the already demonstrated nearest neighbor entanglement, it brings versatility in the design of quantum core units coherently connected via a quantum mediator. A possible implementation of this quantum mediator would be to prepare an entangled state and shuttle individual electron spins across the structure, provided that this transport preserves the entanglement.

In this work, we demonstrate the fast and coherent transport of electron spin qubits across a 6.5 μm long channel, in a GaAs/AlGaAs laterally defined nanostructure. Using the moving potential induced by a propagating surface acoustic wave, we send sequentially two electron spins initially prepared in a spin singlet state. During its displacement, each spin experiences a coherent rotation due to spin-orbit interaction, over timescales shorter than any decoherence process. By varying the electron separation time and the external magnetic field, we observe Ramsey-like interferences which prove the coherent nature of both the initial spin state and the transfer procedure.

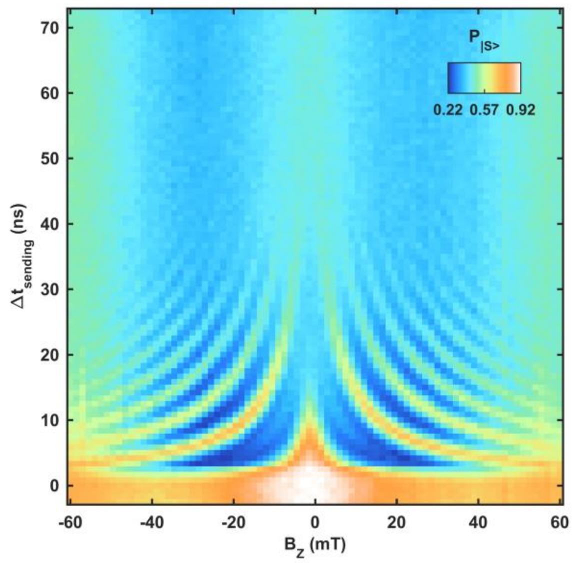



*Figure 1 : Spin-singlet probability as a function of the external magnetic field and the sending delay between the two electrons. The observed oscillations are a signature of the Larmor precession when the two electrons are separated, and their contrast is given by the spin-orbit interaction seen by the electrons during their transport.*

We show that this experiment is analogous to a Bell measurement, allowing us to quantify the entanglement between the two electron spins when they are separated, and proving this fast and long-range qubit displacement is an efficient procedure to share entanglement across future large-scale structures.

[1] P.-A. Mortemousque, E. Chanrion, B. Jadot, H. Flentje, A. Ludwig, A. D. Wieck, M. Urdampilleta, C. Bauerle, and T. Meunier, arXiv:1808.06180 (2018).

[2] B. Bertrand, S. Hermelin, S. Takada, M. Yamamoto, S. Tarucha, A. Ludwig, A. D. Wieck, C. Bauerle, and T. Meunier, Nature Nanotechnology 11, 672 (2016).

# High-quality entanglement on a silicon chip

Dorian Oser[1], Sébastien Tanzilli[2], Florent Mazeas[2], Carlos Alonso Ramos[1], Xavier Le Roux, Laurent Vivien[1], Éric Cassan[1], and Laurent Labonté[2]*
[1]*Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Sud, Université Paris-Saclay, France*
[2]*Université Côte d'Azur, CNRS, Institut de physique de Nice, France*

Combining quantum and integrated photonics gives the ability of generating, manipulating, and detecting individual quantum states on single chips. One of the major challenge is the on-chip rejection of the pump which contaminate the quantum pair generated by non-linear process. The integration on a single substrate of both a photon-pair generator and a pump-rejection filter showing a pump rejection of at least 80 dB is reported. We show two-photon interference fringes with a raw visibility exceeding 92% over 11 complementary channels pairs spanning from both S and C telecom bands along with a coincidence-to-accidental ratio reaching 60. All wavelengths are compatible with the ITU channels and with telecom components.

Our approach is based on multimode Bragg filters. Their limitation is the saturation due to fabrication mismatch and defects [1]. To avoid this problem we use a multimode filter [2] that reflects the fundamental mode into a higher order mode (Fig.1), which is radiated away from the single-mode waveguide (shown in blue in Fig. 1) connecting successive Bragg filters. These properties finally allow to cascade filters by breaking the phase coherence between successive filters, avoiding the rejection saturation.

The photon pairs produced by the source are naturally energy-time entangled as they are produced by spontaneous four-wave mixing (SFWM). Entanglement is analyzed thanks to a folded Franson arrangement consisting of a single unbalanced fiber Michelson interferometer. The integrated filter combined with a ring yields a brightness of 390 pairs/s/MHz with a raw visibility higher than >95 %, and a rate of 480 pairs per seconds for simultaneously two signal/idler pairs. Only a 20dB-crosstalk demultiplexing was added after the chip to achieve these performances, on top of the integrated filter. We extend our investigations according the same methodology for subsequent paired-channels within the S-band and the full C-band. The raw visibilities for all the paired-channels exceeds 92% for an internal rate $\geq 1$ MHz.

This on-chip all-passive photon-pair source is an important step towards the full integration of telecom quantum circuits. This system strong promises for quantum key distribution networks as a cheap source of entangled photon pairs. It is a first step towards a large scale and multi-user QKD network.

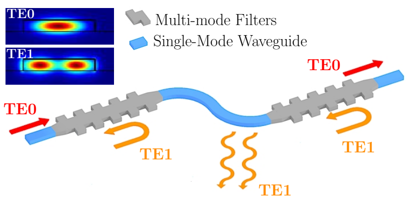



Fig. 1 : Schematic view of proposed cascaded filter. Fundamental mode ($TE_0$) is back-reflected into first order mode ($TE_1$). Single-mode waveguide sections separating adjacent filters radiate the back-reflected $TE_1$ mode away, precluding coherent interaction among different stages.

[1] D. Oser *et al.*, Subwavelength engineering and asymmetry : two efficient tools for sub-nanometer-bandwidth silicon Bragg filters, Optics letters 43, 3208–3211 (2018).

[2] D. Oser *et al.*, Coherency-broken Bragg filters : surpassing on-chip rejection limitations, LPR, doi : 10.1002/lpor.201800226

* laurent.labonte@univ-cotedazur.fr

# Quantum storage of one-photon and two-photon Fock states with an all-optical quantum memory

Benjamin Pointard[1], Viviane Cotte[1], and Rosa Tualle-Brouri[1]*
[1]*Laboratoire Charles Fabry,Institut d'Optique Graduate School, 2 avenue Augustin Fresnel,91120 Palaiseau, France*

Quantum information science requires quantum states engineering where, in the optical domain, photon-number states play a primary role. Using these states in hybrid protocols, which combine discrete and continuous variables for the quantum description of light, one can create many non-classical states such as Schrödinger cat states (SCSs) [2**?** ]. $(|\psi_{cat}>\propto(|\alpha>\pm|-\alpha>))$ However most applications using those states need on-demand and high-rate production.

To achieve this, we implemented an efficient all-optical quantum memory in order to store and release, on demand, quantum states with negative Wigner function. (Fig. 1)

Our experiment starts with a mode-locked Ti :Sapphire (3ps, 850nm, 76MHz repetition rate), and we use two resonant bow-tie cavities first for second harmonic generation, and then for photon pairs production by optical parametrical amplification. The cavities allow an exaltation of the pump beams and of the subsequent non-linear effects. The two beams of the parametric fluorescence take different spatial ways : one part leads to two avalanche photodiodes, which allow the heralding of single-photon and two-photon states [3] ; the second part leads to our optical quantum memory. Our memory consists in a high-finesse cavity with a low-loss insertion/extraction system. The latter is constituted of a Pockels cell and a polarizing beamsplitter. This device allows us to store and release on demand the optical states that we have just created.

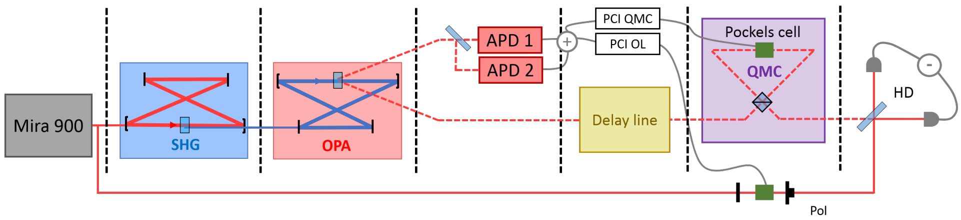



FIGURE 1: Experimental Setup

The Wigner Functions of the released states show negativity after $\sim 0.75\mu s$ and $\sim 0.61\mu s$ respectively for the single-photon and two-photons Fock states [4].

The storage of non-Gaussian states with more than one photon in the Continuous-Variable regime was, to our knowledge, first demonstrated using this setup by our team. We believe that, in the quantum optics domain, this method can offer an ef ?cient tool for the preparation of more complex states such as large amplitude SCSs[2]. This represents a crucial step towards hybrid quantum protocols.

[1] A. Ourjoumtsev, H. Jeong, R. Tualle-Brouri, and P. Grangier, "Generation of optical Schrödinger cats from photon number states," Nature, 448, 784-786 (2007).
[2] J. Etesse, M. Bouillard, B. Kanseri, and R. Tualle-Brouri, "Generation of squeezed Schrödinger cat states with an operation allowing iterative growth," Phys. Rev. Lett, 114(19), 193602 (2015).
[3] A. Ourjoumtsev, R. Tualle-Brouri, and P. Grangier, Physical review letters 96, 213601 (2006).
[4] M. Bouillard, G. Boucher, J. Ferrer Ortas, B. Pointard, and R. Tualle-Brouri, "Quantum Storage of Single-Photon and Two-Photon Fock States with an All-Optical Quantum Memory", Phys. Rev. Lett. 122, 210501 (2019).

* benjamin.pointard@institutoptique.fr

# An irreversible qubit-photon coupling for the detection of itinerant microwave photons

E. Albertinale [1], L. Balembois [1], R. Lescanne [2], E. Billaud [1],
S. Deleglise [3], Z. Leghtas [2], D. Vion [1], D. Esteve [1], P Bertet [1], E Flurin [1]
[1] *Quantronics group, CEA Saclay, France*
[2] *ENS, Paris, France*
[3] *LKB Sorbonne Universite, Paris, France*

Single photon detection is a key resource for sensing at the quantum limit and the enabling technology for measurement based quantum computing [1]. Photon detection at optical frequencies relies on irreversible photo-assisted ionization of various natural materials. However, microwave photons have energies 5 orders of magnitude lower than optical photons, and are therefore ineffective at triggering measurable phenomena at macroscopic scales.

Here, we report the observation of a new type of interaction between a single two level system (qubit) and a microwave resonator. These two quantum systems do not interact coherently, instead, they share a common dissipative mechanism to a cold bath : the qubit irreversibly switches to its excited state if and only if a photon enters the resonator [2]. We have used this highly correlated dissipation mechanism to detect itinerant photons impinging on the resonator. This scheme does not require any prior knowledge of the photon waveform nor its arrival time, and dominant decoherence mechanisms do not trigger spurious detection events (dark counts). We demonstrate a detection efficiency of $58\%$ and a record low dark count rate in the microwave domain of $1.4$ per $\mathrm{ms}$.

This work establishes engineered non-linear dissipation as a key-enabling resource for a new class of low-noise non-linear microwave detectors. It will be applied to direct measurement of relaxation of spin defects in solids, improving state of the art sensitivity and paving the way to quantum information protocols in spin-defects based solid state systems.

[1] R. Raussendorf and H. J. Briegel, PRL,86,22,(2001).

[2] R. Lescanne et al., arXiv :1902.05102 [quant-ph] (2019).

# Fundamental Quantum Aspects (FQA)

# Optimal measurement strategies for fast entanglement detection

Nadia Milazzo[1,2], Daniel Braun[2], and Olivier Giraud[1,3*]
[1] *Institut für theoretische Physik, Universität Tübingen, 72076 Tübingen, Germany*
[2] *LPTMS, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France*

The recent emergence of small quantum processors in quantum information technology has seen the increasing need of characterizing their behavior as "truly" quantum mechanical or not. Already for an unknown quantum state, verifying whether the statistics arising from it can be explained by a classical state is challenging, as long as non-classicality measures or witnesses are based on full tomography. Which is then the most efficient measurement strategy to prove that a state is entangled (or more generally : non-classical) ? We tackle this problem by introducing the statistics of lengths of measurement sequences that allow one to certify entanglement across a given bi-partition of a multi-qubit system over the possible sequence of measurements of random unknown states [1]. Perfectly suited for this approach is the formalism of "truncated moment sequences" [2], that allows one to deal naturally with incomplete information about a quantum state. We use it to identify the best measurement strategy in the sense of the (on average) shortest measurement sequence of (multi-qubit) Pauli-measurements. We find that the set of measurements corresponding to diagonal entries of the moment matrix associated to the state are particularly efficient. For symmetric states their number grows like the third power of the number of qubits and their efficiency increases rapidly with that number.

[1] K. Zyczkowski, K. A. Penson, I. Nechita, and B. Collins, "Generating random density matrices", Journal of Mathematical Physics **52**, 062201 (2011).
[2] F. Bohnet-Waldraff, D. Braun, and O. Giraud, "Entanglement and the truncated moment problem", Phys. Rev. A **96**, 032312 (2017).

* nadia.milazzo@u-psud.fr

# Generating non-classical states of spins coupled to a cavity by optimal collective fields

Quentin Ansel[1], Dominique Sugny[2], and Bruno Bellomo[1]
[1]*Institut UTINAM, CNRS UMR 6213, Université Bourgogne Franche-Comté, Observatoire des Sciences de l'Univers THETA, 41 bis avenue de l'Observatoire, F-25010 Besançon, France*
[2]*Laboratoire Interdisciplinaire Carnot de Bourgogne, CNRS UMR 6303, Université Bourgogne Franche-Comté, BP 47870, F-21078 Dijon, France*

We investigate theoretically the generation of non-classical states of spins coupled to a common cavity by means of a collective driving of the spins. The system is similar to the one considered in recent high sensitivity electron spin resonance experiments [1, 2]. Our purpose is achieved by driving the cavity with coherent and squeezing control fields [3] (see Fig. 1).

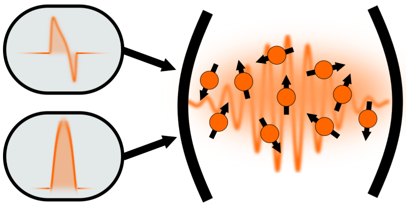


*Fig. 1 : sketch of the system. The state of a spin ensemble coupled to a cavity is modified using a sequence of coherent and squeezing pulses.*

We first analyze the controllability of the system and, using dynamical Lie algebra computation, we show the advantage of using squeezing fields in the generation of unitary transformations. Then, pulse sequences are designed by using numerical control techniques [4] to optimize the generation of different kinds of non-classical states, typically in a minimum time. We consider specific target states, such as symmetric and antisymmetric states, but also the maximization of a measure of non-classicality. Calculations are performed with ensembles of two and four spins. We also investigate to which extent optimal control fields can reduce the detrimental effect of cavity damping. We find that symmetric and antisymmetric states can be generated only asymptotically, but a good fidelity can be reached for control duration longer than the longest Rabi-oscillation period of the spin ensemble. For these specific examples, the use of a squeezing field leads to qualitatively similar results than the ones obtained using only coherent control. Additionally, we highlight the existence of an optimal value of the detuning parameter to generate antisymmetric states and find that the process is highly limited by the cavity damping (even in the good cavity regime). Finally, we show that optimizations using a measure of non-classicality can enhance the entanglement process in situations where a simple state-to-state transfer is limited. In this case, the squeezing field provides a considerable gain [5].

[1] A. Bienfait *et al.*, "Magnetic Resonance with Squeezed Microwaves", Phy. Re. X **7**,041011 (2017).
[2] S. Probst *et al.*, "Shaped pulses for transient compensation in quantum-limited electron spin resonance spectroscopy", J. of Mag. Res. **303**, 42 (2019).
[3] C. W. Gardiner and A. S. Parkins, "Driving atoms with light of arbitrary statistics", Phys. Rev. A **50**, 1792 (1994)
[4] S. J. Glaser *et al.*, "Training Schrödinger's cat : quantum optimal control", Eur. Phys. J. D **69**, 279 (2015).
[5] Q. Ansel, D. Sugny, and B. Bellomo, *in preparation*.

## Learning Algebraic Models of Quantum Entanglement [1]

Hamza Jaffali[1] and Luke Oeding[2*]
[1] *Femto-ST, Optics, University of Bourgogne-Franche Comté, Belfort, France*
[2] *Department of Mathematics and Statistics,*
*Auburn University, Auburn, AL, USA*

Quantum Information and Quantum Computing are two emerging areas of research, and are on their way to revolutionize our conception and implementation of computations. Recently, many efforts were deployed to unite Quantum Information, Quantum Computing and Machine Learning. They have largely been centered on integrating quantum algorithms and quantum information processing into machine learning architectures [2].

Our approach is quite the opposite. We use Machine Learning techniques to study and classify Quantum Entanglement, a key ressource in Quantum Computing. In our work, we train Artificial Neural Networks to learn algebraic varieties, defined by polynomial equations, that characterize and describe different entanglement classes for pure states [3].

Inspired by the work of Breiding *et al.* [4], we focus on determining the membership of a state to an algebraic variety, instead of determining the defining intrinsic equations. By sampling tensors living inside and outside a given algebraic variety, we are able to train ReLU networks to classify such tensors. In the case of varieties defined by homogeneous polynomials, we also design and train hybrid polynomial networks [5].

We give examples for detecting separable states, degenerate states, as well as border rank classification for up to 5 qubits and 3 qutrits.

[1] Hamza Jaffali and Luke Oeding. *Learning Algebraic Models of Quantum Entanglement*. (2019). arXiv preprint arXiv :1908.10247.
[2] Iordanis Kerenidis, Jonas Landman, Alessandro Luongo, and Anupam Prakash. *q-means : A quantum algorithm for unsupervised machine learning*. (2018). arXiv preprint arXiv :1812.03584.
[3] Frédéric Holweck, Jean-Gabriel Luque and Jean-Yves Thibon. *Geometric descriptions of entangled states by auxiliary varieties*. (2012). Journal of Mathematical Physics, 53(10), 102203.
[4] Paul Breiding, Sara Kalisnik, Bernd Sturmfels, and Madeleine Weinstein. *Learning algebraic varieties from samples*. (2018). Revista Matematica Complutense **31** , no. 3, 545–593.
[5] Joe Kileel, Matthew Trager, and Joan Bruna. *On the expressive power of deep polynomial neural networks*. (2019). arXiv preprint arXiv :1905.12207.

* hamza.jaffali@utbm.fr, oeding@auburn.edu

# Cooling a spin ensemble with a cavity

Bartolo Albanese[1], Sebastian Probst[1],Vishal Ranjan[1], Denis Vion[1], Emmanuel Flurin[1], Daniel Esteve[1], Patrice Bertet[1*]
[1]*Quantronics Group, SPEC, CEA, Universite Paris-Saclay, France*

Electron spin resonance (ESR) spectroscopy is widely employed for the detection and characterization of paramagnetic species and their magnetic and chemical environment [1]. In ESR the spins precessing around an applied static magnetic field are first excited by microwaves and subsequently emit a signal into an inductively coupled resonant cavity. A high degree of polarization is essential to maximize the signal. Hyperpolarization techniques based on optical pumping have been developed in the past decades but the requirements on the optical properties limit their range of application. Here we present a new universal hyperpolarization scheme based on radiative cooling, where a spin ensemble in the mode volume of a cavity is thermalized to a black body radiation colder than the sample. For spins in free space spontaneous emission of photons is orders of magnitude slower than any other relaxation process. However, by coupling the spins to a cavity of small mode volume and low loss rate it is possible to reach the regime in which radiative relaxation is the fastest thermalization process [2], as predicted by Purcell [3].

The spin system under study is an ensemble of bismuth donors implanted into a host silicon crystal and inductively coupled to a high quality factor superconducting niobium resonator. The sample is installed at the 900 mK stage of a dilution cryostat while the resonator is coupled via a switch either to a 20 mK or to a 900 mK thermal source. When the switch is connected to the colder black body, the electronic spins are cooled via radiative relaxation while the silicon crystal remains at 900 mK, leading to an increase of ESR signal by more than a factor 2.

[1] A. Schweiger and G. Jeschke, "Principles of Pulse Electron Paramagnetic Resonance", Oxford University Press, **225**, (2001).
[2] A. Bienfait, "Controlling spin relaxation with a cavity", Nature, **531**, 74-77, (2016).
[3] E. Purcell, "Spontaneous Emission Probabilities at Radio Frequencies", Phys. Rev., **69**, 681, (1946).

* patrice.bertet@cea.fr

## Two-body collisions in the time-of-flight dynamics of lattice Bose superfluids

Antoine Tenart[1], Cécile Carcy[1], Hugo Cayla[1], Gaétan Hercé[1], Marco Mancini[1], and David Clément[1*]
[1]*Laboratoire Charles Fabry – Institut d'Optique Graduate School – Palaiseau (France)*

We investigate two-body collisions occurring during the time-of-flight expansion of interacting three-dimensional lattice Bose superfluids. The number of collisions is extracted from the observed s-wave scattering halos located between the diffraction peaks of the superfluids. These faint halos can be monitored thanks to the large dynamical range in densities associated with detecting individual metastable Helium atoms. We monitor the number of collisions as a function of the total atom number and of the amplitude of the lattice, in a regime where the number of trapped atoms per lattice site is large. In addition, we introduce a classical model of collisions that quantitatively describes the experiment without adjustable parameters. Finally, the present work validates quantitatively the assumption of a ballistic expansion when investigating the Bose-Hubbard Hamiltonian with unity occupation of the lattice.

[1] Cayla, H., et al. "Single-atom-resolved probing of lattice gases in momentum space." Physical Review A 97 061609 (2018).
[2] Bouton, Q., et al. "Fast production of Bose-Einstein condensates of metastable helium." Physical Review A 91 061402 (2015).
[3] Ziń, P., et al. "Quantum multimode model of elastic scattering from Bose-Einstein condensates." Physical review letters 94 200401(2005).

* david.clement@institutoptique.fr

# Entanglement transfer in a quantum network by local counting of identical particles

Alessia Castellini[1], Bruno Bellomo[2], Giuseppe Compagno[1], and Rosario Lo Franco[1,3]
[1]*Dipartimento di Fisica e Chimica - Emilio Segrè, Università di Palermo, via Archirafi 36, 90123 Palermo, Italy*
[2]*Institut UTINAM, CNRS UMR 6213, Université Bourgogne Franche-Comté, Observatoire des Sciences de l'Univers THETA, 41 bis avenue de l'Observatoire, F-25010 Besançon, France*
[3]*Dipartimento di Ingegneria, Università di Palermo, Viale delle Scienze, Edificio 6, 90128 Palermo, Italy*

Quantum information and communication processing within quantum networks usually employs identical particles. Despite this, the physical role of quantum statistical nature of particles in large-scale networks remains elusive. This is due to the fact that, in these processes, spatial overlap of the wave functions typically does not occur in the relevant places so that the identical particles are distinguishable and behave like nonidentical ones.

Here, we present a new conceptual process of entanglement transfer in a large-scale quantum network which is fundamentally activated by indistinguishability of particles. We employ an approach based on spatially localized operations and classical communication (sLOCC), where single-particle local measurements are made onto assigned spatial regions [1]. The standard entanglement swapping with distinguishable particles necessitates to start from entangled particle pairs and requires final Bell measurements [2]. Differently, the present process, for identical fermions, enables remote entanglement among distant nodes with no distribution of initial entangled pairs and without performing Bell measurements. The process exploits the natural entanglement due to spatially overlapping identical particles by using local counting of independently-prepared identical particles [3].

In particular, we first study the basic process which serves as the elementary step for the extension to a many-node quantum network. As displayed in Fig. 1, we take four identical fermions (two pairs), prepared by four independent (space-like separated) sources $\{\mathrm{S}_i,\ i = 1, ..., 4\}$. Each particle is sent to the corresponding beam splitter $\mathrm{BS}_i$. The two sources $\mathrm{S}_1$ and $\mathrm{S}_2$ independently prepare two fermions with opposite pseudospin. Each beam splitter sends the particle with the same amplitude into two separated sites A and M, so that each particle is in the same delocalized spatial mode $|\alpha\rangle = (|\mathrm{A}\rangle + |\mathrm{M}\rangle)/\sqrt{2}$. Similarly, sources $\mathrm{S}_3$ and $\mathrm{S}_4$ generate the fermions of the second pair with opposite pseudospin in the delocalized spatial mode $|\beta\rangle = (|\mathrm{M}\rangle + |\mathrm{B}\rangle)/\sqrt{2}$. The modes $|\alpha\rangle$ and $|\beta\rangle$ then partially overlap in the shared intermediate node M. We show how to use postselection by sLOCC to leave two fermions with opposite pseudospins in the central node M and two entangled fermions in the extreme nodes, A and B. We then extend this procedure to the case of a many-node quantum network and finally compare this process to that with bosons and to a process involving separated intermediate sites [3].

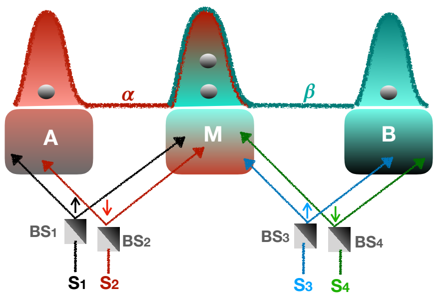



*Fig. 1: scheme for the entanglement transfer by four independently-prepared indistinguishable fermions.*

[1] R. Lo Franco and G. Compagno, "Indistinguishability of Elementary Systems as a Resource for Quantum Information Processing", Phys. Rev. Lett. **120**, 240403 (2018).
[2] M. Żukowski, A. Zeilinger, M. A. Horne, and A. K. Ekert, "“Event-ready-detectors” Bell experiment via entanglement swapping", Phys. Rev. Lett. **71**, 4287 (1993).
[3] A. Castellini, B. Bellomo, G. Compagno, and R. Lo Franco, "Activating remote entanglement in a quantum network by local counting of identical particles", Phys. Rev. A **99**, 062322 (2019).

A spin-photon interface : measuring a single spin with a single photon

Clément Millet[1], Paul Hilaire[1,2], Juan Loredo[1], Carlos Antón[1], Abdelmounaim Harouri[1], Aristide Lemaître[1], Isabelle Sagnes[1], Daniel Lanzillotti-Kimura[1], Olivier Krebs[1], Niccolo Somaschi[1], Pascale Senellart[1] and Loïc Lanco[1,2*]
[1]*Centre de Nanosciences et de Nanotechnologies, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91120 Palaiseau,*
[2]*Université Paris Diderot – Paris 7, 75205 Paris Cedex 13, France*

The development of future quantum networks requires an efficient interface between stationary and flying qubits. A promising approach is to use micropillars to deterministically couple a single photon with the spin of a single charge trapped in a semiconductor quantum dot (QD). Previous measurements with non-electrically contacted devices evidenced a macroscopic rotation of polarization induced by a single spin [1]. We have also developed a tomography technique to reconstruct the full quantum state of reflected photons, first demonstrated with neutral QDs [2]. In this work, we develop an efficient spin-photon interface by deterministically coupling a QD to an electrically contacted micropillar cavity [3], in a device geometry already used for the demonstration of high quality single-photon sources [4]. The resulting giant spin-dependent polarization rotation allows mapping the quantum state of the spin qubit with that of the photon polarization qubit.

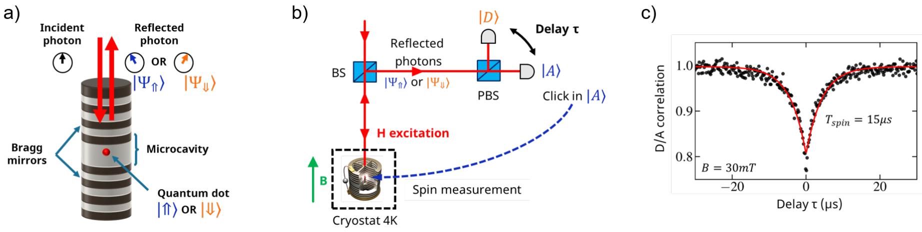



Fig. 1. (a) Polarization rotation by a micropillar cavity coupled to a charged QD. (b) Experimental cross-correlation setup. (c) Cross-correlation measurement between the A and D polarizations. The measurement back-action by a single detected photon in polarization A modifies the spin state probabilities from 50% - 50% to typically 75% - 25%. This effect lasts for a characteristic spin lifetime of $15\mu s$.

The QD-cavity system is excited with a linearly polarized continuous wave laser and the reflected photons are rotated clockwise or counter-clockwise, leading to different polarization states $|\Psi_\Uparrow\rangle$ and $|\Psi_\Downarrow\rangle$ depending on the spin state. The cross-correlation measurements between photon detections in the antidiagonal and diagonal polarizations (Fig. 1(b)) demonstrate that the first photon partially measures the spin, leading to a decrease in photon counts in the complementary polarization, and thus to anticorrelations between A and D detectors (Fig 1(c)). Such giant spin-photon interaction opens the road towards numerous perspectives in terms of spin physics (cavity-enhanced spin noise spectroscopy), fundamental quantum measurements (from measurement-induced decoherence to the Quantum Zeno effect) and quantum communication applications (from spin-photon and multi-photon entanglement to deterministic quantum gates).

[1] C. Arnold et al, "Macroscopic rotation of photon polarization induced by a single spin", Nat. Commun. **6**, 6236 (2015).
[2] C. Antón et al, "Tomography of the optical polarization rotation induced by a single quantum dot in a cavity", Optica **4**, 1326-1332 (2017).
[3] P. Hilaire et al, "Deterministic assembly of a charged quantum dot-pillar cavity device ", arXiv :1909.02440 [quant-ph] (2019).
[4] N. Somaschi et al, "Near-optimal single-photon sources in the solid state", Nat. Photon. **10**, 340-345 (2016).

* clement.millet@c2n.upsaclay.fr

# Adiabatic Elimination and Sub-space Evolution of Open Quantum Systems


Ibrahim Saideh[1], Daniel Finkelstein-Shapiro[2], and Arne Keller[1,3*]

[1] *Univ. Paris-Saclay, Univ. Paris Sud, 91405 Orsay, France*

[2] *Division of Chemical Physics, Lund University, Box 124, 221 00 Lund, Sweden*

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


The task of simulating open quantum systems capturing every detail possible is quite taxing and one is usually only interested in the reduced picture rather than the whole one. Efficient descriptions of open quantum systems can be obtained by performing an adiabatic elimination of the fast degrees of freedom and formulating effective operators for the slow degrees of freedom in reduced dimensions.

For the case of closed quantum systems, adiabatic elimination is a standard tool to obtain an effective Hamiltonian for the relevant subspace. However, it is not the case for open quantum systems where state evolution is not governed by a unitary operator but rather by a completely positive trace preserving map. Among those maps, the ones that are generated by a Lindblad operator are of special importance since they allow to have a generic mathematical form that captures any interaction with the environment. When the Lindblad dynamics present two time scales, different methods have been developed to perform the adiabatic elimination of the fast degrees of freedom [1, 2] such that the dynamics of the slow density matrix is generated by an effective Lindblad operator. As a consequence, the dynamics of the slow density matrix is trace preserving and is only valid for the case where exchange of population between the fast and slow degrees of freedom is negligible.

In this work [3], we use Feshbach projectors $\mathcal{P}$ and $\mathcal{Q} = \mathbb{1} - \mathcal{P}$ [4] to develop a general strategy to approximate the evolution of $\mathcal{P}\rho(t)$, the slow component of the quantum state $\rho(t)$ at time $t$. It is based on the the projection $\mathcal{P}G(z)\mathcal{P}$ of the resolvent $G(z) = (z - L)^{-1}$ of the original Lindblad operator $L$ in the slow subspace. We define $L_{\text{eff}}(z)$, a $z$-dependent operator defined on the slow subspace only, such that $\mathcal{P}G(z)\mathcal{P} = (z - L_{\text{eff}}(z))^{-1}$. The operator $L_0 = L_{\text{eff}}(z = 0)$ is the analog of the effective Lindblad operator obtained previously in Refs. [1, 2]. Furthermore, we also show how to correct the trace preserving evolution generated by $L_0$ to take into account possible population exchange between fast and slow subspace.

In this work, we consider only the case where the projector $\mathcal{P}$ onto the space of operators themselves defined on $\mathcal{H}$ is built from a projector $P$ onto the underlying Hilbert space $\mathcal{H}$ as $\mathcal{P}\rho = P\rho P$. In others words, we assume that the fast/slow partition is linked to a partition of $\mathcal{H}$ in two complementary subspaces $\mathcal{H} = P\mathcal{H} \oplus Q\mathcal{H}$. The application of our formalism to bipartite systems where the fast/slow partition is linked to a tensorial structure $\mathcal{H} = \mathcal{H}_{\text{slow}} \otimes \mathcal{H}_{\text{fast}}$ will be the subject of a future publication. We apply our general result to several examples where the fast subspace is finite or infinite dimensional. In the last case, we consider that the Hamiltonian of the fast part has a continuous spectrum while the slow part has a discrete one. In other words, we address the problem of adiabatic elimination of the continuous set of states in dissipative Fano [5] systems. In the wide band approximation, corresponding to a "flat continuum", we are able to obtain the explicit expression for $L_{\text{eff}}(z)$ and therefore analyze in great detail the adiabatic approximation. In particular we show formally and numerically that in the limit where the fast dynamics reaches its steady state in a very short time, the Hamiltonian of the fast part can be approximated by a flat continuous spectrum.


[1] M. Mirrahimi and P. Rouchon, IEEE Transactions on Automatic Control 54, 1325 (2009)

[2] F. Reiter and A. S. Sørensen, Phys. Rev. A 85, 032111 (2012).

[3] D. Finkelstein-Shapiro, D. Viennot, I. Saideh, T. Hansen, T. Pullerits, and A. Keller, arXiv :1909.04211 [quant-ph] (2019).

[4] H. Feshbach, Annals of Physics 19, 287 (1962).

[5] U. Fano, Phys. Rev. 124, 1866 (1961).

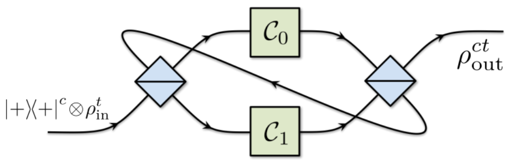


* ibrahim.saideh@u-psud.fr

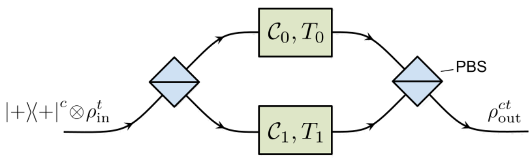
# Communication through coherent control of quantum channels

Alastair A. Abbott[1], Julian Wechs[2], Dominic Horsman[3], Mehdi Mhalla[3], and Cyril Branciard[2]
[1]*Département de Physique Appliquée, Université de Genève, 1211 Genève, Switzerland*
[2]*Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France*
[3]*Univ. Grenoble Alpes, CNRS, Grenoble INP, LIG, 38000 Grenoble France*

Coherent control of quantum operations – as in the CNOT gate – is a crucial resource for quantum computation and communication. Recently, there has been interest in whether other forms of coherent control might be useful for information processing. A particularly novel example is the quantum switch [1] (Fig. (a)), a device that coherently controls the order in which two operations are applied and provides an example of "causally indefinite" computation. Recently, it was shown that this type of coherent control of causal orders can lead to a new type of advantage in quantum communication, called *causal activation*. A stark example of this is the ability to use the quantum switch to transmit information through two completely depolarizing (and thus zero-capacity) channels [2].




(a) The quantum switch




(b) Coherently controlled channels

While intriguing, the role of causal indefiniteness in this effect remained unclear. In this contribution we address this problem by consider a simpler scenario (Fig. (b)) where one simply coherently controls between the two quantum channels to be applied, thereby decoupling the role of coherent control from that of causal indefiniteness [3].

We show that a similar activation effect is possible even in this simpler scenario: one can transmit information through two coherently controlled completely depolarizing channels, despite the absence of any causal indefiniteness [3]. We generalize this result to show other activation effects, proving that one can also activate quantum capacity by coherently controlling dephasing channels, and quantifying the capacity of the global induced channel in such scenarios. These results show the potential of coherent control of channels (as opposed to the more well-studied control of unitaries) for quantum information processing.

Motivated by these observations, we then study the coherent control of channels more generally. We find, perhaps counterintuitively, that the action of coherently controlled channels depends not only on their description as completely positive trace-preserving (CPTP) maps, but also on finer aspects of their implementation (e.g., as purified unitary interactions with local environments). We explain this phenomenon and show that the channels' description as CPTP maps must be supplemented by "transformation matrices" to fully specify their action when controlled coherently, and we provide a method to characterize the obtainable transformation matrices for any given channel.

Although this "implementation-dependence" shows the necessity for a finer description of channels when used in certain settings, it can also be seen to open up new possibilities in quantum information. As an example, we show that it allows two different implementations of a quantum channel to be distinguished, a possibility with potential applications for error correction and channel security. More generally, our approach provides a path towards defining a more general type of "quantum if statement" for quantum computation and generalized models of quantum computation that can provide advantages over the standard circuit approach [3, 4].

[1] G. Chiribella, G. M. D'Ariano, P. Perinotti, and B. Valiron, Phys. Rev. A **88**, 022318 (2013).
[2] D. Ebler, S. Salek, and G. Chiribella, Phys. Rev. Lett. **120**, 120502 (2018).
[3] A. A. Abbott, J. Wechs, D. Horsman, M. Mhalla, and C. Branciard, (2018), arXiv:1810.09826 [quant-ph].
[4] G. Chiribella, and H. Kristjánsson, Proc. R. Soc. A **475**, 20180903 (2019).

# Continuous-variable nonlocality and contextuality.

Rui Soares Barbosa[1,3], Tom Douce, Pierre-Emmanuel Emeriau[2*], Elham Kashefi[2,3] and Shane Mansfield[2]
[1]*Department of Computer Science, University of Oxford*
[2]*Laboratoire d'Informatique de Paris 6, CNRS, Sorbonne Université*
[3]*School of Informatics, University of Edinburgh*
[*]*pierre-emmanuel.emeriau@lip6.fr*

Contextuality is one of the principal non-classical behaviours that can be exhibited by quantum systems. The Heisenberg uncertainty principle identified that certain pairs of quantum observables are incompatible, e.g. position and momentum. In operational terms, observing one will disturb the outcome statistics of the other. Imprudent commentators will sometimes cite this as evidence that position and momentum cannot simultaneously be assigned definite values. However, this is not quite right and a more careful conclusion is that we simply cannot observe these values simultaneously. To make a stronger statement requires contextuality. Roughly speaking, the latter is present whenever the behaviour of a system is inconsistent with the basic assumptions that *(i)* all of its observable properties may be assigned definite values at all times, and *(ii)* jointly performing compatible observables does not disturb the global value assignment. Aside from its foundational importance, today contextuality is increasingly studied as the essential ingredient for enabling a range of quantum-over-classical advantages in informatic tasks, which include the onset of universal quantum computing in certain computational models.

To date the study of contextuality has largely focused on discrete variable scenarios and that the main frameworks and approaches to contextuality are tailored to modelling these. In such scenarios, observables can only take values in discrete, and usually finite, sets. Discrete variable scenarios arise in finite-dimensional quantum mechanics, e.g. when dealing with quantum registers in the form of systems of multiple qubits as is common in quantum information and computation theory.

Yet, from a practical perspective, continuous-variable quantum systems are emerging as some of the most promising candidates for implementing quantum informational and computational tasks. The main reason for this is that they offer unrivalled possibilities for deterministic generation of large-scale resource states and for highly-efficient measurements of certain observables. Together these cover many of the basic operations required in the one-way or measurement-based model of quantum computing for example. Typical implementations are in optical systems where the continuous variables correspond to the position-like and momentum-like quadratures of the quantised modes of an electromagnetic field. Indeed position and momentum as mentioned previously in relation to the uncertainty principle are the prototypical examples of continuous variables in quantum mechanics.

The main contributions are the following : *(i)* We present a robust framework for contextuality in continuous-variable scenarios that follows along the lines of the discrete-variable framework introduced by Abramsky and Brandenburger [2]. *(ii)* We show that the Fine–Abramsky–Brandenburger theorem [1, 2] extends to continuous variables. This establishes that noncontextuality of an empirical behaviour, originally characterised by the existence of deterministic hidden-variable models, can equivalently be characterised by the existence of a factorisable hidden-variable models, and that ultimately both of these are subsumed by a canonical form of hidden-variable model – a global section in the sheaf-theoretic perspective. An important consequence is that nonlocality may be viewed as a special case of contextuality in continuous-variable scenarios just as for discrete-variable scenarios. *(iii)* The contextual fraction, a quantifiable measure of contextuality that bears a precise relationship to Bell inequality violations and quantum advantages [3], can also be defined in this setting using infinite linear programming. It is shown to be a non-increasing monotone with respect to the free operations of a resource theory for contextuality [3]. Crucially, these include the common operation of binning to discretise data. A consequence is that any witness of contextuality on discretised empirical data also witnesses and gives a lower bound on genuine continuous-variable contextuality. We show that the dual program computes a generalised Bell inequality that is optimised to the empirical model. *(iv)* While the infinite linear programs are of theoretical importance and capture exactly the quantity and inequalities we are interested in, they are not directly useful for actual numerical computations. To get around this limitation, we introduce a hierarchy of semi-definite programs which are relaxations of the original problem [4], and whose values converge monotonically to the contextual fraction. Hence we develop an automated way to compute the contextual fraction and its corresponding generalised Bell inequality in a continuous-variable setting.

[1] A. Fine Arthur, "Hidden variables, joint probability, and the Bell inequalities", Physical Review Letters 48(5), p.291 (1982).

[2] S. Abramsky and A. Brandenburger, "The sheaf-theoretic structure of non-locality and contextuality", New Journal of Physics 13(11) (2011).

[3] S. Abramsky, R.S. Barbosa, and S. Mansfield, "Contextual fraction as a measure of contextuality", Physical Review Letters 119(5) (2017)

[4] J-B. Lasserre, "Moments, positive polynomials and their applications", Imperial College Press (2009).

# Scaling the spatial fluctuations in LDOS in finite-sized photonic crystals

Priya[1] and Rajesh V. Nair[2*]

[1]*Centre de Nanosciences et de Nanotechnologies, Centre National de la Recherche Scientifique, Université Paris-Sud, Université Paris-Saclay, 10 Boulevard Thomas Gobert, 91120 Palaiseau, France*

[2]*Laboratory for Nano-scale Optics and Metamaterials (LaNOM), Department of Physics, Indian Institute of Technology Ropar, Rupnagar, Punjab 140001, India*

Photonic crystals are artificially engineered with a periodic spatial variation of refractive index on an optical wavelength scale to exhibit exotic optical phenomena that have rewarding applications in lasing, solid-state lighting, reflectors, etc [1]. The periodicity in the structure leads to the formation of photonic stop gap that hinders the propagation of certain wavelengths through the crystal due to optical Bragg diffraction. The photonic stop gaps vary for the propagation direction and polarization of incident light. The stop gap modifies the local density of photon states (LDOS) of the environment. The redistribution of LDOS in the stop gap region manifests significant changes in the emission properties of an embedded emitter as stated by the Fermi's golden rule. Theoretically, LDOS is reduced to zero inside the stop gap for an ideal photonic crystal of an infinite size [1]. However, in a real photonic crystal the change in LDOS is undermined due to its finite-size [2] and intrinsic disorder. Therefore, the extent of modification of spontaneous emission in real synthesized photonic crystals has always been a topic of interest.

Due to its ease of fabrication, three-dimensional self-assembled photonic crystals are customarily explored to study stop gaps. The crystal is composed of micron-sized spherical particles self-organized into close packed face cantered cubic symmetry with (111) plane as its growth direction [3]. The stop gap in the normal incident direction is a consequence of Bragg diffraction from family of (111) plane. The crystal is grown with grain boundaries which divide the sample into micron-sized defect-free regions called domains. The optimized growth conditions forms domains of an average size 100µm × 100µm. The light propagation and emission is precisely measured from a single domain of the crystal by home-built experimental setups [4]. The microscopic studies unveil an exemplary increase in the optical response from a single domain. The LDOS is modified strongly for single domain as authenticated by the redistribution spontaneous emission intensity and lifetime. The single domain spontaneous emission measurements highlight a spatial variation in LDOS due to the finite size of the crystal domain. The experimental results reveal that the suppression in LDOS scales linearly with the finite-size of the domain as predicted by the theory [5].

[1] E. Yablonovitch, "Inhibited Spontaneous Emission in Solid-State Physics and Electronics", Phys. Rev. Lett. **58**, 2059 (1987).

[2] D. M. Whittaker, "Inhibited emission in photonic woodpile lattices", Opt. Lett. **25**, 779 (2000).

[3] C. Lopez , "Material aspects of photonic crystals", Adv. Mater. **15**, 1679 (2003).

[4] S. Sharma, Priya, S. K. Saini, and R. V. Nair, "A versatile micro-reflectivity setup for probing the optical properties of photonic nanostructures", Rev. Sci. Instrum. **90**, 023103 (2019).

[5] S. B. Hasan, A. P. Mosk, W. L. Vos, and A. Lagendijk, "Finite-size Scaling of the density of states in photonic band gap crystals", Phys. Rev. Lett. **120**, 237402 (2018).

# Sub-GHz linewidths ensembles of SiV centers in a diamond nano-pyramid revealed by charge state conversion

Clément Pellet-Mary[1], Louis Nicolas[1], Tom Delord [1], Paul Huillery [1], and Gabriel Hétet[1]*
[1] *Laboratoire de Physique de l'Ecole normale supérieure, ENS, Université PSL, CNRS, Sorbonne Université, Université Paris-Diderot, Sorbonne Paris Cité, Paris, France*

Efficient interfaces between two-level emitters and photons are key components of quantum networks and sensing. $SiV^-$ centers embedded into a diamond nanostructure are promising for such purpose. We have studied photoluminescence properties at cryogenic temperatures of diamond AFM probes [1,2] and observed photochromism of a very dense ensemble of $SiV^-$ centers consisting in trapping into a dark state under resonant excitation when nitrogen impurities are present. We suppose that this effect is a charge state switching between negatively charged and neutral SiV charge states. This effect is used to perform persistent hole burning which reveals very low homogeneous broading, only twice the lifetime limit. It is promising for quantum optics experiments and paves the way to sub-wavelength microscopy technics.

We will also present our latest results on the Zeeman splitting and possible lifetime measurement of the $SiV^-$ $1/2$ spin.

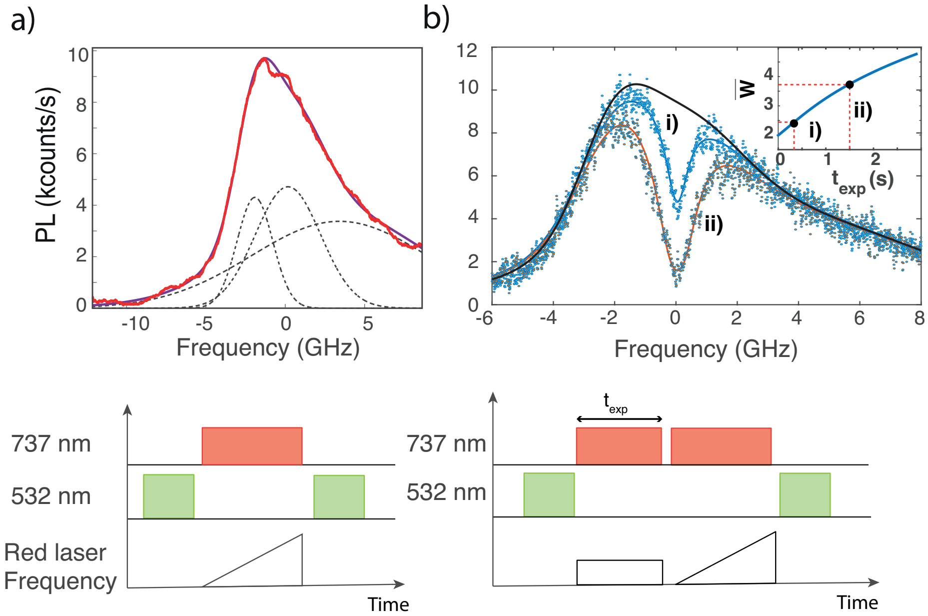



**Figure 1.** a) Averaged PLE measured at 6K by scanning the resonant laser at 737 nm around an electronic transition transition in the presence of green laser light between scans. b) PLE spectra after three different exposure times at 6K : in black without hole burning, in blue $t_{exp}$ = 300 ms and in orange, $t_{exp}$ = 1500 ms. The dots represent raw data and the continuous lines are fitted data. Here $P_{737}$= 0.877 $\mu$W. The inset shows the width of the holes $\Gamma_h$ inferred from the fit and normalized to the homogeneous linewidth $\Gamma_e$(W= $\Gamma_h/\Gamma_e$).

[1] AR. Nelz et al., Applied Physics Letters, 109, 19, 193105, (2016).
[2] L. Nicolas et al., AIP Advances, 8, 6, 065102, (2018).

* clement.pellet-mary@phys.ens.fr

# Single photon conversion between site-controlled quantum dots and photonic optical waveguides

Xiaolun Xu[1*], Ali Issa[1], Aurélie Broussier[1], Muhammad H. Muhammad[1,2], Fabien Geoffray[2], Safi Jradi[1], Christophe Couteau[*1], Sylvain Blaize[*1]

[1] Laboratory Light, nanomaterials & nanotechnologies (L2n), Charles Delaunay Institute CNRS. University of Technology of Troyes, 12 rue Marie Curie, 10004 Troyes Cedex, France

[2] Teem Photonics,61 Chemin du Vieux Chêne, 38246 Meylan, France.

xiaolun.xu@utt.fr , christophe.couteau@utt.fr , sylvain.blaize@utt.fr

Manipulating and detecting single quantum objects are major technical challenges during the second quantum revolution. Our work focus on deterministic integrating quantum dots (QDs) at preselected position on quantum devices. The well-controlled QDs-polymer nanostructures were fabricated simply at room-temperature utilizing developed direct laser writing (DLL) [1]. Subsequently, the size and photoluminescence (PL) characterization results make possible for creating single QD by carefully adjusting the laser writing parameters and QDs concentration of photopolymer liquids. In conjunction with ion exchanged waveguides (IEWs), we successfully detected the waveguide-coupled emission of quantum dots by our home build PL measurement setup. Our results show the potential of our integration technique for future quantum photonic devices and single photon detection approaches [2].

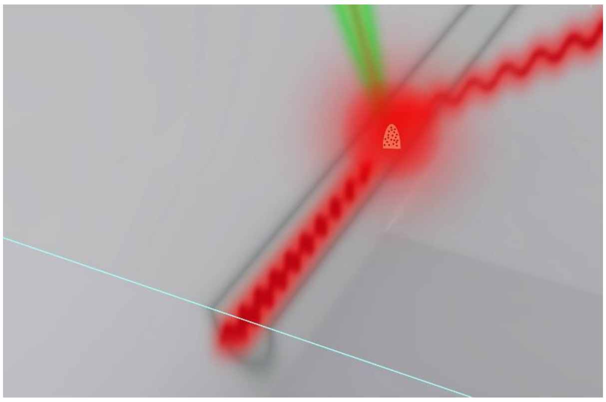


Figure 1. Schematic of a single photon coupling between well-located QDs and an optical waveguide.

[1] Lio G E, Madrigal J B, Xu X, et al. Integration of Nanoemitters onto Photonic Structures by Guided Evanescent-Wave Nano-Photopolymerization[J]. The Journal of Physical Chemistry C, 2019.

[2] Stefano Pierini, Mackrine Nahra, Christophe Couteau, et al. Nanophotonic approaches towards quantum integrated photonics, Submitted to <advanced quantum technologies>.

# Implementable Hybrid Entanglement Witness

Gaël Massé[1], Thomas Coudreau[1], Arne Keller[1] and Perola Milman[1*]
[1] *QITE Team, Université de Paris, Laboratoire Matériaux et Phénomènes Quantiques, CNRS, F-75013, Paris, France*

Light is studied by many research groups in order to process or transport quantum information. This information can be encoded in Discrete Variables (DV) such as photon numbers, or in Continous Variables (CV) such as quadratures of the electromagnetic field.

Both variables present specific advantages and drawbacks: while DV experiments show high fidelities, their efficiencies are low, and the contrary applies for CV experiments [1]. It has been foreseen that hybridization between DV and CV states can combine advantages and lead to deterministic teleportation with high fidelities and unambiguous state discrimination. Quantum information tasks using this technique are currently being developed both theoretically and experimentally [2].

The goal of this work is to present an implementable hybrid entanglement witness. Entanglement lies at the heart of quantum physics and is a key ressource for quantum information and computation [3]. Its characterisation is thus of crucial importance and has been studied extensively, notably with so-called entanglement witnesses (EW) [4]. For our purpose, we will focus on the ability of EWs to detect entanglement on experiments with a very short set of measurements.

The system we study is described by the following wave function [5] :

$$|\psi\rangle = \frac{|0\rangle\,|\text{cat}-\rangle + |1\rangle\,|\text{cat}+\rangle}{\sqrt{2}}, \tag{1}$$

where $|\text{cat}\pm\rangle = \frac{|\alpha\rangle \pm |-\alpha\rangle}{N^{\pm}(\alpha)}$ with $|\alpha\rangle$ a coherent state. We show that $W = \frac{1}{2}I - |\psi\rangle\langle\psi|$, is a witness robust to noise for our system. We implement a general noise model which mixes states on each channel with delocalized photons. We express the action of noise into the state using Krauss formalism

$$\rho_{\text{full noise}} = \sum_{i,j=1}^{2} \left(\mathscr{C}_i \otimes \mathscr{D}_j\right) \rho \left(\mathscr{C}_i^{\dagger} \otimes \mathscr{D}_j^{\dagger}\right) \tag{2}$$

and we identify the continuous ($\mathscr{C}$) and discrete ($\mathscr{D}$) Krauss operators as forming respectively amplitude-damping channels and a mix of amplitude damping and dephasing channels. We find a basis [6] in which $W$ forms a lower bound of an entanglement measure, the concurrence, and then we use this basis to express $W$ using hybrid observables only. They display the property of being easily measurable with homodyne detectors. The final witness, which is still robust to noise, is

$$W_f = 1 - \frac{1}{2}\left[1 + \sigma_X \otimes \frac{a + a^{\dagger}}{n_x(\eta_x)} - \sigma_Y \otimes \frac{i(a - a^{\dagger})}{n_y(\eta_y)}\right] \tag{3}$$

where $n_x$ and $n_y$ are normalisation factors. We give a protocol that enables detection of hybrid entanglement on existing set-ups.

[1] P. Van Loock, "Optical hybrid approaches to quantum information." Laser Photon. Rev. **5** 167-200 (2011)
[2] Y. Lim, J. Joo, T. P. Spiller, and H. Jeong, "Loss-resilient photonic entanglement swapping using optical hybrid states", Phys.Rev.A **94**, 062337(2016).
[3] R. Horodecki, P. Horodecki, M. Horodecki, and K. Horodecki, "Quantum Entanglement", Rev. Mod. Phys. **81**, 865 (2009)
[4] D. Chruscinski, G. Sarbicki, "Entanglement witnesses: construction, analysis and classification", J. Phys. A: Math. Theor., **47** 4830012014, (2014)
[5] O. Morin et al, "Remote creation of hybrid entanglement between particle-like and wave-like optical qubits", Nature Photonics **8** 570–574 (2018)
[6] K. Kreiss, "Classifying, quantifying, and witnessing qudit-qumode hybrid entanglement", Phys.Rev.A, **85**, 032307 (2012)

* gael.masse@univ-paris-diderot.fr

# Bipartite nonlocality with a many-body system

Enky Oudot, Jean-Daniel Bancal, Pavel Sekatski and Nicolas Sangouard
*Quantum Optics Theory Group, University of Basel, CH-4056 Basel, Switzerland*[*]

Detecting non locality has been achieved only for small systems and one of the fundamental questions which remains open is : Can we detect non locality in large system with current technology ?

In the submitted paper we address this question by considering two ensembles of spin $\frac{1}{2}$ which are measured collectively. We go beyond restriction on the number of measurements which have been presented in [1]. We give numerical arguments supporting the conjecture that in this scenario no Bell inequality can be violated for arbitrary numbers of spins and large number of measurements if only first order moment observables are available. These measurements correspond to the classical magnetization measurement we can perform on macroscopic system.

By releasing the constraint on the measurements, we then propose a Bell test on a state which have been implemented in practice with a Bose-Einstein-Condensate [2] in order to demonstrate non locality in many-body bipartite systems. This Bell test can also be implemented on various states which have been experimentally realized. We found that such test require a parity measurements which highlights the strong requirements needed to detect bipartite quantum correlations in many-body systems device-independently, which is interesting for fundamental aspect of quantum science and possibly for using many body system for quantum information tasks.

[1] Ramanathan R, Paterek T, Kay A, Kurzyński P, and Kaszlikowski D 2011, *Phys. Rev. Lett.* **107**, 060405 (2011)

[2] Schmied R, Bancal J D, Allard B, Fadel M, Scarani V, Treutlein P, Sangouard N 2016, *Science* **352**, 441

* enky.oudot@unibas.ch

# Orbital Angular Momentum of light : interplay with atoms by Four Wave Mixing

A. CHOPINAUD[1,2], M. JACQUEY[2], B. VAIRIS DE LESEGNO[2], and L. PRUVOST[2*]
[1] *Department of Physics, University of Strathclyde 107 Rottenrow East, Glasgow, United Kingdom*
[2] *Laboratoire Aimé Cotton, CNRS, U-PSUD, ENSPS, Univ Paris-Saclay campus d'Orsay, 91405 Orsay, France*

The orbital angular momentum of light (OAM) is a quantized variable, which is explored for quantum technologies, its key strength being a wide set of values offering a large basis for encoding and entanglement. With experiments realized in a rubidium vapour we explore the interplay between optical vortices and atoms to determine the rules for the OAM exchange and to realize quantum memories, vortex-pairs, OAM-conversion or OAM operations.

Using Four Wave Mixing in rubidium (Fig.1), we have studied the vortex-conversion from red OAM inputs at 780 and 776 $nm$, to the output photon pair at 420 $nm$ and 5.23 $\mu m$, in order to explore the efficiency and the selection rules associated to the OAM exchange.

In the case of inputs with one vortex at 776 nm, with a large set of OAMs having azimuthal numbers $\ell$ from -30 to 30, we have shown a wide band for the conversion efficiency,a good mode quality of the output blue beam, and an OAM transfer mainly to the blue output. It is explained by phase matchings and the output wavelengths ratio [1–3].

With two input coaxial vortex beams we have explored the OAM summation rules and, shown that the output strongly depends on the relative sign of the input OAMs [4]. It is explained by phase-matchings and by the overlap of the involved light beams.

This work opens to applications like creation and manipulation of for multi vortex pairs.

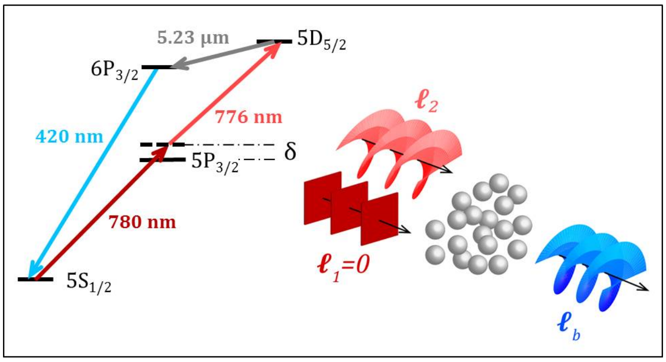



Fig. 1 :principle of vortex conversion based on the two-photon Raman excitation in rubidium.

[1] A. Chopinaud, M. Jacquey, B. Viaris de Lesegno and L. Pruvost, Phys Rev A 2018, Phys. Rev. A. **97**, 063806 (2018). See also
[2] G. Walker, A. S. Arnold, and S. Franke-Arnold, Phys. Rev. Lett. **108**, 243601 (2012).
[3] A. M. Akulshin, et al., Opt. Lett. **40**, 1109 (2015).
[4] A. Chopinaud, M. Jacquey, B. Viaris de Lesegno and L. Pruvost, submitted.

* laurence.pruvost@u-psud.fr

# Quantum Communication & Cryptography (QCOM)

# Sub-second optical storage in an atomic frequency comb memory using dynamical decoupling

Adrian Holzäpfel, Jean Etesse, Krzysztof T. Kaczmarek, Alexey Tiranov, Nicolas Gisin, Mikael Afzelius*
*Department of Applied Physics, University of Genva, CH-1211 Geneva 4, Switzerland*

The development of devices like quantum memories is nowadays very active, as their existence opens prospects as well for the implementation of a quantum network as for the possibility to synchronize quantum resources [1]. However, the information stored in those memories always suffers from limited lifetime due to inevitable interactions with the environment.
Rare-earth ion doped crystals are very good candidates to implement these quantum memories, as the information can be stored in very protected degrees of freedom, limiting the aforementioned loss mechanisms. Even further, it has been recently shown that coherence times of up to 6 hours could be reached in europium doped YSO [2], by using dynamical decoupling sequences under specific magnetic field configurations called 'ZEFOZ' points.
Following these observations, we have investigated the effect of dynamical decoupling sequences on an optical storage sequence using the atomic frequency comb protocol [3] under a weak magnetic field configuration. Thanks to a study previously conducted in our group [4], the direction as well as the magnitude of the field could be precisely chosen to prevent loss of efficiency of the protocol, and could help to push the storage time from 1 ms [5] to up to 530 ms [6]. Analysis of the noise model is also conducted, and reveals that our spin ensembles are subject to Ornstein-Uhlenbeck [7] process linked with fluctuation of the Yttrium spin bath.
These observations open new prospects in the possibility to use rare-earth ion doped crystals for long-term quantum information storage and manipulation.

[1] N. Sangouard, C. Simon, H. de Riedmatten and N. Gisin, Rev. Mod. Phys. **83**, 33 (2011).
[2] M. Zhong *et al.* Nature **517**, 177-181 (2015).
[3] M. Afzelius, C. Simon, H. de Riedmatten and N. Gisin, Phys. Rev. A **79**, 052329 (2009).
[4] E. Zambrini-Cruzeiro, J. Etesse, A. Tiranov, P.-A. Bourdel, F. Fröwis, P. Goldner, N. Gisin and M. Afzelius, Phys. Rev. B **97**, 094416 (2018).
[5] P. Jobez, C. Laplane, N. Timoney, N. Gisin, A. Ferrier, P. Goldner and M. Afzelius, Phys. Rev. Lett. **114**, 230502 (2015).
[6] A. Holzäpfel, J. Etesse, K. T. Kaczmarek, A. Tiranov, N. Gisin and M. Afzelius, *in prep*.
[7] J. R. Klauder and P. W. Anderson Phys. Rev. **125**(3) 912-932 (1962).

* jean.etesse@unige.ch

# Discrete/continuous variables hybrid entanglement with time-bin coding

Élie Gouzien,[1,*] Floriane Brunel,[1] Sébastien Tanzilli,[1] and Virginia D'Auria[1]

[1]*Université Côte d'Azur, Institut de Physique de Nice (INPHYNI), CNRS UMR 7010, Parc Valrose, 06108 Nice Cedex 2, France*

Light as proven to be an excellent support to carry as well as manipulate Quantum Information, especially in the perspective of practical quantum technologies [1]. Traditionally, information have been coded in two distinct ways. With the "discrete variable" approach, "qubits" are coded in discrete spectrum observables, usually using Fock states with only one or few photons, eventually spread on several modes of the electromagnetic field [2]. "Continuous variables" approach relies on continuum spectrum observables, such as the electric field. Information is typically coded on the phase of a coherent state, a squeezing angle or the relative phase between the two components of a Schrödinger cat [3]. Discrete variables benefit from tolerance to losses but generation and detection are probabilistic. Continuous variables allow deterministic generation and measurement but largely suffer from losses. Hybrid discrete/continuous variables entangle discrete and continuous variable subsystems. They permit designing protocols that take the advantages of both coding strategies by limiting their individual drawbacks [4]. For instance, protocols have been identified to distribute entanglement [5], achieve almost deterministic quantum teleportation [6], entanglement swapping [7, 8] and computation [9].

Experimental realizations of photonic hybrid states have already been accomplished, where the discrete part is either encoded using the presence or absence of a photon [10, 11] or on single photon polarization states [12, 13]. For practical applications in telecom fibers, none of those strategies is fully satisfactory ; single-rail encoding suffer from losses and detector inefficiency while polarization is not maintained during propagation [1].

We present an experimental scheme to generate hybrid entanglement, with the discrete part coded in the time-bin observable. Our proposal is based on the interference between an optical Schrödinger cat and a time-bin entangled pair of photons, followed by single-photon measurement. Conveniently, we stress that the hybrid state is heralded and doesn't require any post-selection process. We also analyse the impact of experimental imperfections on the generation scheme and demonstrate that our scheme is robust against the presence of vacuum and multiple pair generation in the discrete part input, thus allowing to work with standard photon pair sources based on non-linear optical process. Schrödinger cats are difficult to generate, usually involving probabilistic steps [14]. Instead, squeezed vacuum states can be used as input of out generation scheme ; we analyse in detail the consequences of such a strategy for the heralding rate and quality of the generated hybrid state.

[1] N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, Reviews of Modern Physics **74**, 145 (2002).
[2] T. E. Northup and R. Blatt, Nature Photonics **8**, 356 (2014).
[3] G. Adesso, S. Ragy, and A. R. Lee, Open Systems & Information Dynamics **21**, 1440001 (2014).
[4] U. L. Andersen, J. S. Neergaard-Nielsen, P. van Loock, and A. Furusawa, Nature Physics **11**, 713 (2015).
[5] J. B. Brask, I. Rigas, E. S. Polzik, U. L. Andersen, and A. S. Sørensen, Physical Review Letters **105** (2010), 10.1103/PhysRevLett.105.160501.
[6] S.-W. Lee and H. Jeong, Physical Review A **87** (2013), 10.1103/PhysRevA.87.022326.
[7] R. C. Parker, J. Joo, M. Razavi, and T. P. Spiller, Journal of Optics **19**, 104004 (2017).
[8] Y. Lim, J. Joo, T. P. Spiller, and H. Jeong, Physical Review A **94** (2016), 10.1103/PhysRevA.94.062337.
[9] P. van Loock, W. J. Munro, K. Nemoto, T. P. Spiller, T. D. Ladd, S. L. Braunstein, and G. J. Milburn, Physical Review A **78** (2008), 10.1103/PhysRevA.78.022303.
[10] H. Jeong, A. Zavatta, M. Kang, S.-W. Lee, L. S. Costanzo, S. Grandi, T. C. Ralph, and M. Bellini, Nature Photonics **8**, 564 (2014).
[11] O. Morin, K. Huang, J. Liu, H. Le Jeannic, C. Fabre, and J. Laurat, Nature Photonics **8**, 570 (2014).
[12] H. Kwon and H. Jeong, Physical Review A **91** (2015), 10.1103/PhysRevA.91.012340.
[13] D. V. Sychev, A. E. Ulanov, E. Tiunov, A. A. Pushkina, A. Kuzhamuratov, V. Novikov, and A. I. Lvovsky, Nature Communications (2018), 10.1038/s41467-018-06055-x.
[14] A. Ourjoumtsev, H. Jeong, R. Tualle-Brouri, and P. Grangier, Nature **448**, 784 (2007).

* elie.gouzien@unice.fr

# Polarization of Quantum Channels using Clifford-based Channel Combining

Frédéric Dupuis[1a,1b], Ashutosh Goswami[2], and Mehdi Mhalla[1,3], Valentin Savin[4]
[1a] *Université de Lorraine, CNRS, Inria, LORIA, F-54000 Nancy, France*
[1b] *Université de Montréal, Québec, Canada*
[2] *Univ. Grenoble Alpes, Grenoble INP, LIG, F-38000 Grenoble, France*
[3] *Univ. Grenoble Alpes, CNRS, Grenoble INP, LIG, F-38000 Grenoble, France*
[4] *CEA-LETI, MINATEC, F-38054 Grenoble, France*

Channel coding that is transmitting information reliably using a noisy channel, is one of the important problems in information theory. Polar coding proposed by Arikan [2] is a way to do channel coding for transmitting classical information. In fact, polar codes are the first explicit construction of a family of codes that provably achieve the channel capacity for any binary-input, symmetric, memoryless channel. Arikan's construction is based on a channel combining and splitting procedure, where a CNOT gate is used to combine two instances of the transmission channel. When the channel combining and splitting is applied recursively on many instances of a channel, this allows one to synthesise so called virtual channels, which tend to become either noiseless (good channels) or completely noisy (bad channels), a phenomenon known as "channel polarization". Then channel polarization is effectively exploited by transmitting messages via the good channels, while freezing the inputs to the bad channels to the values known to both encoder and decoder.

Polar codes have been generalized for the transmission of classical information over quantum channels in [3], and for transmitting quantum information in [4, 5]. It was shown in [4] that the recursive construction of polar codes using a CNOT polarizes in both amplitude and phase bases for Pauli and erasure channels, and [5] extended this to general channels. Then, a CSS-like construction was used to generalize polar codes for transmitting quantum information. One very important question that is raised in [4], "is it possible to construct a purely quantum polar codes, where one can synthesise virtual quantum channels which become good and bad as a quantum channel ?" We answer the above question positively in this paper by proving quantum channel polarization for qubit-input channels [1]. More precisely, we provide a purely quantum version of polar codes, achieving the coherent information of any quantum channel. Our scheme relies on a recursive channel combining and splitting construction, where a two-qubit gate randomly chosen from the Clifford group is used to combine two single-qubit channels. The inputs to the synthesized bad channels are frozen by preshared EPR pairs between the sender and the receiver, so our scheme is entanglement assisted. We further show that quantum polarization can be achieved by choosing the channel combining Clifford operator randomly, from a much smaller subset of only 9 two-qubit Clifford gates. Subsequently, we show that a Pauli channel polarizes if and only if a specific classical channel over four symbol input set polarizes. We exploit this equivalence to prove fast polarization for Pauli channels, and to devise an efficient successive cancellation based decoding algorithm for such channels. Finally, we present a code construction based on chaining several quantum polar codes, which is shown to require a rate of preshared entanglement that vanishes asymptotically.

**Note : An earlier version of this paper has been presented at IEEE Information Theory Workshop (ITW), 2019**

[1] F. Dupuis, A. Goswami, M. Mhalla, V. Savin, Polarization of Quantum Channels using Clifford-based Channel Combining, arXiv : 1904.04713.

[2] E. Arikan, "Channel polarization : A method for constructing capacity-achieving codes for symmetric binary-input memoryless channels." IEEE Transactions on information Theory **55.7**, 3051-3073 (2009).

[3] M. M. Wilde, S. Guha, "Polar Codes for Classical-Quantum Channels", Information Theory, IEEE Transactions on **59.2** 1175–1187 (2013).

[4] J. M. Renes, F. Dupuis, and R. Renner, "Efficient Polar Coding of Quantum Information", Physical Review Letters **109**, 050504 (2012).

[5] J. M. Renes and M. M. Wilde, "Polar Codes for Private and Quantum Communication Over Arbitrary Channels", IEEE Transactions on Information Theory **60.6**, 3090–3103 (2014).

# Quantum Information Processing using Hybrid Entanglement of Light

Tom Darras[1], Huazhuo Dong[1], Adrien Cavaillès[1], Giovanni Guccione[1],
Hanna Le Jeannic[2], Jérémy Raskop[1], Kun Huang[3], and Julien Laurat[1*]
[1]*Laboratoire Kastler Brossel, Sorbonne Université, CNRS,*
*ENS-PSL Université, Collège de France, 4 Place Jussieu, 75005 Paris, France*
[2]*Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen, Denmark*
[3]*Shanghai Key Laboratory of Modern Optical Systems,*
*and Engineering Research Center of Optical Instruments and Systems,*
*School of Optical Electrical and Computer Engineering,*
*University of Shanghai for Science and Technology, Shanghai 200093, China*

The wave-particle duality of light has led to two different encodings of optical quantum information. One approach, refered as the discrete-variable (DV) one, relies on finite dimensional quantum systems, while the other one, refered as the continuous-variable (CV) one, is based on wave-like states belonging to an infinite dimensional Hilbert space. These two encodings have historically been separated, but recently, new hybrid protocols which aim at combining the two complementary encodings have emerged [1]. In that prospect our recent demonstration of the measurement-induced generation of hybrid entanglement between discrete and continuous-variable quantum states generated using optical parametric oscillators [2], located at distant places and connected by a lossy channel, has opened the way to the implementation of hybrid protocols and heterogeneous quantum networks. Here we will report the first protocols based on this resource : the remote preparation of continuous-variable qubits [3], and a violation of an Einstein-Podolosky-Rosen steering inequality [4].

Based on heralded hybrid entanglement, we first implemented a remote state preparation scheme, where CV states are generated at a distance. By conditioning on the quadrature measurement on the DV mode at a given phase of the local oscillator, we experimentally succeeded in remotely preparing arbitrary superpositions of coherent states, i.e. CV qubits, with fidelities above 80% with the target states, including odd cat states exhibiting negative values of the Wigner function. We also realized the first demonstration of EPR-steering using hybrid entanglement between CV and DV optical qubits. A steering test free of post-selection is implemented using homodyne detection, and steering is experimentally assessed through quantum tomography by the violation of a suitable steering inequality determined using semi-definite programming. The violation of the optimum steering inequality by more than 5 standard deviations makes our system applicable to one-sided independent quantum communication security protocols. Finally we will relate ongoing efforts towards teleportation-based protocols in this hybrid framework.

[1] U. L. Andersen, J. S. Neergaard-Nielsen, P. van Loock, and A. Furusawa, "Hybrid discrete- and continuous-variable quantum information", Nat. Physics **11**, 713 (2015).
[2] O. Morin, K. Huang, J. Liu, H. Le Jeannic, C. Fabre, and J. Laurat, "Remote creation of hybrid entanglement between particle-like and wave-like optical qubits", Nat. Photonics **8**, 570 (2014).
[3] H. Le Jeannic, A. Cavaillès, J. Raskop, K. Huang, and J. Laurat, "Remote preparation of continuous-variable qubits using los-tolerant hybrid entanglement of light", Optica **5**, 1012-1015 (2018).
[4] A. Cavaillès, H. Le Jeannic, J. Raskop, G. Guccione, D. Markham, E. Diamanti, M. D. Shaw, V. B. Verma, S. W. Nam, and J. Laurat, "Demonstration of Einstein-Podolsky-Rosen steering using hybrid continuous-and discrete-variable entanglement of light", Phys. Rev. Lett. **121**, 170403 (2018).

* julien.laurat@upmc.fr

# Distributing resources over quantum networks

Jens Eisert[2], Frédéric Grosshans[6,1], Damian Markham[1], Clément Meignant[1,2], and Alexander Streltsov [3,4,5]

[1] *Laboratoire d'Informatique de Paris 6, CNRS, Sorbonne Université, 4 place Jussieu, 75005 Paris, France*

[2] *Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany*

[3] *Centre for Quantum Optical Technologies IRAU, Centre of New Technologies, University of Warsaw, Banacha 2c, 02-097 Warsaw, Poland*

[4] *Faculty of Applied Physics and Mathematics, Gdańsk University of Technology, 80-233 Gdańsk, Poland*

[5] *National Quantum Information Centre in Gdańsk, 81-824 Sopot, Poland*

[6] *Laboratoire Aimé Cotton, CNRS, Univ. Paris-Sud, ENS Cachan, Univ. Paris-Saclay, 91405 Orsay Cedex, France*

The study of quantum networks is a recent active field of quantum information with promising applications, ranging from secure communication, clock synchronization, exponential gains in communication complexity, distributed sensing to delegated computation [1–3] etc. Distributing quantum states over all kinds of quantum networks is a necessary step to implement most of these applications and will consume quantum resources which may be difficult to replenish. It is thus necessary to find optimal ways of managing resources over a quantum network. We represent the quantum network by a multipartite entangled state and study how to convert it into states useful for the previously presented applications.

We present here a work on this issue in two different but related settings. In both, states are shared by distant parties that can perform local operations on their parts and communicate between themselves classically for free. We first study the asymptotic rate of conversion between arbitrary multipartite pure states. We report substantial progress on the old question [4, 5] of the rate at which GHZ and other multipartite states can be asymptotically distilled from arbitrary pure states. We show that for $N+1$-partite pure states $\psi^{AB_1\dots B_N}$ and $\sigma^{AB_1\dots B_N}$ both shared by one (arbitrarily chosen) party we will call Alice and $N$ parties we will all call Bob, the optimal Local Operation and Classical Communication (LOCC) conversion rate is bounded as

$$\min_X \frac{S(\psi^X)}{S(\sigma^X)} \geq R(\psi^{AB_1\dots B_N} \to \sigma^{AB_1\dots B_N}) \geq \min_X \left\{ \frac{S(\psi^{AX})}{\sum_{B_i \notin X} S(\sigma^{B_i})} \right\}, \tag{1}$$

where $X$ denotes a subset of all Bobs. The already known upper bound follows from the fact that any multipartite LOCC protocol is also bipartite with respect to any of the bipartitions. Our lower bound can be optimized by taking the maximum over all possible choices of Alice, giving a theorical minimum of the cost regarding the distribution of multipartite entangled states and the conversion between different resource-states over a quantum network with perfect quantum memory.

We then investigate the distribution of crossed EPR pairs through a ring network (see Figure 1) in a single-shot setting. Such a setting tends to be more realistic than the asymptotic one as allocated resources and memory available for protocols over a quantum network implementation will be limited. This conversion is particularly relevant, the asymptotic rate of conversion from the square to the cross is equal to one. However, we prove an impossibility to do the conversion in a single-shot setting, even if the asymptotic rate is attained for two copies. The question of the feasability of those conversions is closely linked to notion of distribution over a quantum network and we have good hope that the proof of impossibility presented would give insights at a theory to distribute quantum states over a low-resource quantum network.

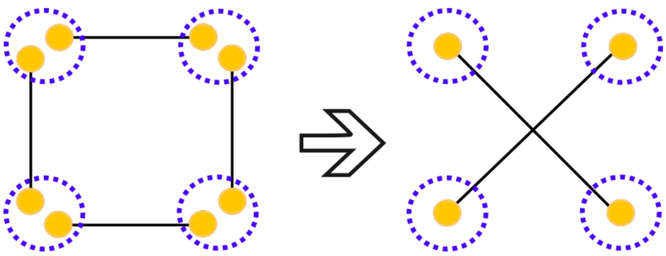


FIGURE 1. Square quantum network to cross EPR transformation. Here, each circle represents a qubit and each edge a maximally entangled pair.

[1] Č. Brukner, M. Żukowski, J.-W. Pan, and A. Zeilinger, Physical review letters **92**, 127901 (2004).

[2] R. Jozsa, D. S. Abrams, J. P. Dowling, and C. P. Williams, Physical Review Letters **85**, 2010 (2000).
[3] R. Raussendorf, D. E. Browne, and H. J. Briegel, Physical review A **68**, 022312 (2003).
[4] P. Vrana and M. Christandl, J. Math. Phys. **56**, 022204 (2015).
[5] P. Vrana and M. Christandl, Commun. Math. Phys. **352**, 621 (2017).

# Quantum dot based single photon sources : performance reproducibility

H. Ollivier[1], I. Maillette[1], G. Coppola[1], S . Wein[2], P. Hilaire[1], A. Harouri[1], A. Lemaître[1],I. Sagnes[1], L. Lanco[1],4, S . Thomas[1], J. Loredo[1], C. Anton[1], N. Somaschi[3], P. Senellart[1]*
[1]*Centre de Nanosciences et Nanotechnologies, CNRS, 91120 Palaiseau, France*
[2]*IQST and Department of Physics and Astronomy, University of Calgary, Canada*
[3]*Quandela, SAS, 86 rue de Paris, 91400 Orsay, France*
[4]*Université de Paris, Centre for Nanoscience and Nanotechnology (C2N), F-91120 Palaiseau, France*

Quantum dots are promising candidates to generate the single photons needed to implement quantum networks. Although quantum dot indistinguishable single photon sources have already allowed an exponential speedup of quantum optics experiments,such as Boson Sampling, so far only single photons emitted by one quantum dot source have been used. Indeed, it remains to demonstrate that this technology can be reproducibly fabricated for widespread applications, an important challenge since quantum dots show natural inhomogeneity. In this presentation, we show that it is possible to produce multiple sources presenting homogeneous characteristics (operating at similar wavelengths, with comparable temporal shapes, and with consistently high efficiency, single-photon purity and indistinguishability). We benchmark the performances of a dozen sources and highlight the path towards scaling up quantum dot single-photon technology to implement the fundamental blocks for the development of future large-scale quantum networks.

Our sources are composed of quantum dots deterministically embedded in semiconductor micropillar cavities [1]. The quantum dot behaves as an artificial atom producing single photons that are efficiently collected by the cavity. We fabricate them in a deterministic and reproducible way, assuring high single-photon purity, indistinguishability and brightness [2].

We study two types of sources, corresponding to two optical transitions, based on either a neutral or a charged exciton. We discuss the physical phenomena at play rendering differences in single-photon source performance. We also propose new techniques to identify the source type and discuss how to improve their performances [3].

[1] N. Somaschi et al., Nat. Photon. 10, 340 (2016).
[2] A. Nowak et al., Nat. Commun. 5, 3240 (2014).
[3] H. Ollivier et al., submitted (2019).

* first.last@institution.com

# Quantum coherent control of $N$ channels : communication enhancement in an indefinite causal order scenario

**Lorenzo M. Procopio[1], Francisco Delgado[2], Marco Enríquez[2], Nadia Belabas[1], Juan Ariel Levenson[1]**
*1. Centre for Nanoscience and Nanotechnology, C2N, CNRS, Université Paris-Sud, Université Paris-Saclay, 91120 Palaiseau, France*
*2. Escuela de Ingeniería y Ciencias, Tecnológico de Monterrey, CP.52926, Atizapán, México*

In the quantum Shannon theory, the current paradigm of quantum communications, enhancement of information transmission is obtained through quantum superposition and quantum entanglement. Up to now the carriers and the channels of information benefited of the full quantum paraphernalia but the connections between channels remained classical. Recently, a new paradigm for quantum Shannon theory with superposition of trajectories was proposed, where not only the information but also the propagation in space-time is treated quantum mechanically [1]. A remarkable counterintuitive effect was then demonstrated by Chiribella et al [2] and Abbott et al [3] : two completely depolarizing quantum channels, that lose all information when used separately or combined in a classical way, can transmit classical information when they are coherently controlled in time or in space. These results are currently being widely discussed in the theoretical literature [4] and some experimental confirmations have already been given [5-6].

We propose here [7] a general procedure to assess the transmission of information through a network of $N$ channels operated within this new paradigm for quantum information and quantum communication fields. Our work in an indefinite causal order structure goes beyond the state-of-the-art two-channel scheme for communication theory [2-3]. We retrieve information transmission through a network of an arbitrary number $N$ of channels with arbitrary depolarization strengths and obtain a quantitative assessment of the impact of quantum coherent control through indefinite causal structures. Remarkably, we find for example in the case $N = 3$ that the transmission of information for three channels is twice the transmission of the two-channel case when a full superposition of all possible causal orders is used.

Our method also uncovers new quantum features of indefinite causal structures by exhibiting the outcome of coherent control of the number $m$ of causal orders involved in the combination of channels on the transmission of information. This advanced quantum control was not considered in all previous theoretical and experimental studies. This opens the way to optimization and understanding of all the involved parameters.

Our results are of prime importance for optimizing and minimizing resources and for in depth understanding of the efficiency of coherent control of the trajectories. Our method also yielded interesting predictions for the case of $N$ channels. We find that the transmission of information, for the case of two chosen causal orders ($m = 2$), depends on the parity of the number of channels $N$. We also found that for two specific causal orders the transmission of information remains surprisingly constant and equal to the two-channel case as the number of channels increases. Finally, we suggest an optical implementation to test our predictions using standard telecom technology.

[1] G. Chiribella, and Kristjánsson, H. "Quantum Shannon theory with superpositions of trajectories." Proceedings of the Royal Society A 475.2225 (2019) : 20180903.

[2] D. Ebler, S. Salek and G. Chiribella,“Enhanced communication with the assistance of indefinite causal order", Phys. Rev. Lett. 120, 120502 (2018)

[3] A. A. Abbott, J. Wechs, D. Horsman, M. Mhalla, and C. Branciard, “Communication through coherent control of quantum channels", arXiv :1810.09826 (2018)

[4] P.A. Guérin, G. Rubino and C. Brukner, “ Communication through quantum-controlled noise" Physical Review A, 99(6) (2019)

[5] K. Goswami, J. Romero, A. G. White, “Communicating via ignorance", arXiv :1807.07383, (2018)

[6] Y. Guo, X. M. Hu, Z. B. Hou, H. Cao, J. M. Cui, B. H. Liu,Y.F. Huang, C.F. Li and G. C. Guo, “ Experimental investigating communication in a superposition of causal orders", arXiv :1811.07526 (2018)

[7] L.M. Procopio, F. Delgado, M. Enriquez, N. Belabas and J.A. Levenson, “Communication through quantum coherent control of $N$ channels in a multi-partite causal-order scenario" arXiv :1902.01807 (2019).

# Stable and efficient confocal microscope for the commercialization of bright single photon sources under resonant excitation

M. BILLARD[1,2*], F. PASTIER[1], O. ORTIZ[2], M. ESMANN[2], A. BRIEUSSEL[1], V. GIESZ[1], N. SOMASCHI[1], O. KREBS[2] and P. SENELLART[2*]
[1]*Quandela, 10 Bd Thomas Gobert, 91120 Palaiseau, France*
[2]*Centre de Nanosciences et de Nanotechnologies (C2N), 10 Boulevard Thomas Gobert, 91120 Palaiseau, France*

Over the last decade, the constant improvement in performance of solid-state single photon sources has established them as a prime candidate for quantum optics experiments where high flux of pure single photons is required [1]. Individual quantum dots (QD) coupled to optical micropillar cavities are now able to produce a high rate stream of pure and indistinguishable single photons [2] for applications such as Boson sampling [3–5] or sub-shot noise imaging [6]. The growing interest in commercially available single photon sources motivated the development of a microscope with high stability and low losses, to harness the power of state-of-the-art QD devices, while also improving the ease-of-use for non-expert users.

Here, we present an optimized confocal microscope that allows to resonantly excite the QD and to collect the emitted photons in orthogonal polarization (resonance fluorescence regime with extinction ratio of $10^5$). Its main features are a 70% overall photon collection efficiency, much improved compared to previous setups [2] and excellent mechanical stability over several hours.Thanks to it, we obtained a brightness around 8% in the output fiber of the system, a $g^{(2)}$ of 3% and a corrected HOM of 90%. The present microscope is already available for the use of single-photon sources commercialized by Quandela while additional improvements are currently underway in order to further reduce losses as well as to exploit other excitation regimes.

In order to provide a complete plug-and-play single photon source, without needing a low-vibration cryostat and an optical table, we are working on a fibered source where a singlemode fiber is attached to a single pillar. A new system version has been developped and the fisrt results are promissing. New developments are underway to improve the process and thus find the state of the art of our sources.

[1] B. Lounis et al., Rep. Prog. Phys. **68**, 1129-1179 (2005).
[2] N. Somaschi, et al., Nature Photonics **10**, 340–345 (2016)
[3] H. Wang et al., Nature Photonics **11**, 361–365 (2017)
[4] J. C. Loredo et al., Phy. Rev. Lett. **118**, 130503 (2017)
[5] C. Antn et al., Preprint at https://arxiv.org/abs/1905.00936 (2019)
[6] X. L. Chu et al., Nature Photonics **11**, 58–62 (2017)

* marie.billard@quandela.com

# Photorefractive effects in LiNbO3-based integrated-optical circuits for continuous variable experiments

F. Mondain[1], F. Brunel[1], X. Hua [1], E. Gouzien[1], T. Lunghi[1], F. Doutre[1], M.D. Micheli[1], A. Zavatta[2,3], S. Tanzilli[1], V. D'Auria[1]*
[1]*Institut de Physique de Nice, Université Côte d'Azur, CNRS, Parc Valrose, 06108, Nice Cedex 2, France*
[2]*Instituto Nazionale di Ottica (INO-CNR) Largo Enrico Fermi 6, 50125 Florence, Italy*
[3]*LENS and Department of Physics, Università di Firenze, 50019 Sesto Fiorentino, Florence, Italy*

Encoding information on field quadratures of quantum states leads to a wide range of applications including quantum metrology [1], and quantum information science [2]. Quantum communication protocols using Gaussian states such as squeezed states, have been proposed and demonstrated [3]. Furthermore, generation and manipulation of non-Gaussian states is attractive for quantum computing [4].

Out-of-the-laboratory applications requires compact devices, compatible with standard commercial fibers and telecomunication components [5]. Integrated optics for generation and manipulation of quantum states is emerging as an ideal tool to satisfy the demand of scalable and stable components for guided quantum communication networks [6]. In this context, lithium niobate ($LiNbO_3$) is one of the most advanced platforms, featured by an easy coupling with fiber technology, high-nonlinear efficiency, opto-electronical properties and low propagation losses.

At the same time, optical properties of $LiNbO_3$ can be unwittingly modified during experiments due to photorefraction. This phenomenon is a photoinduced charge transport occurring in $LiNbO_3$ subject to strong light field such as those used to pump squeezing experiment. Displaced charges initially, present on intrinsic defects in $LiNbO_3$, change the refractive index of the medium. If not controlled, photorefraction is a source of instability and losses which degrades squeezed states. This unwanted phenomenon then limits on chip generation and manipulation of squeezed states. Accordingly, it is pertinent to investigate how photorefraction impacts the performances of $LiNbO_3$ integrated circuits.

This work studies common operations performed on $LiNbO_3$ integrated photonics and crucial for continuous variable networks. We characterize the impact of photorefraction on directional couplers as those required for wavelength division demultiplexing operation or homodyne detectors. We then investigate influence of photorefraction on spontaneous down conversion in periodically poled $LiNbO_3$ used for squeezing generation. Eventually we analyze photorefraction combined with parasitic cavity effect produced by the input and output facets of the chip. We stress that a deep understanding of photorefractive effects in $LiNbO_3$ is of the most importance to improve chip manufacturing and set the best working conditions.

[1] Petr M. Anisimov, Gretchen M. Raterman, Aravind Chiruvelli, William N. Plick, Sean D. Huver, Hwang Lee, and Jonathan P. Dowling. Quantum metrology with two-mode squeezed vacuum : Parity detection beats the heisenberg limit. *Phys. Rev. Lett.*, 104 :103602, Mar 2010.

[2] Samuel Braunstein and Peter Loock. Quantum information with continuous variables. *Reviews of Modern Physics*, 77, 10 2004.

[3] Akira Furusawa, Jens Lykke Sørensen, Samuel L Braunstein, Christopher A Fuchs, H Jeff Kimble, and Eugene S Polzik. Unconditional quantum teleportation. *Science*, 282(5389) :706–709, 1998.

[4] Alexei Ourjoumtsev, Aurélien Dantan, Rosa Tualle-Brouri, and Philippe Grangier. Increasing entanglement between gaussian states by coherent photon subtraction. *Phys. Rev. Lett.*, 98 :030502, Jan 2007.

[5] Florian Kaiser, Bruno Fedrici, Alessandro Zavatta, Virginia D'Auria, and Sébastien Tanzilli. A fully guided-wave squeezing experiment for fiber quantum networks. *Optica*, 3(4) :362–365, 2016.

[6] Andreas Neyer. Integrated-optic devices in lithium niobate : technology and applications. In *Electro-Optic and Magneto-Optic Materials II*, volume 1274, pages 2–17. International Society for Optics and Photonics, 1990.

* virginia.dauria@unice.fr

# Multipartite entanglement engineering in nonlinear waveguide arrays

David Barral,* Nadia Belabas, Kamel Bencheikh, and Ariel Levenson
*Centre de Nanosciences et de Nanotechnologies C2N, CNRS,*
*Université Paris-Saclay, 10 Boulevard Thomas Gobert, 91120 Palaiseau, France*

Entanglement is a key resource of disruptive quantum technologies and the quest of efficient sources of entanglement is a thriving area of research [1]. Notably, multipartite entanglement is required in a number of quantum computation, simulation and communication protocols. Optical networks are of great interest in this context and nonlinear $\chi^{(2)}$ waveguide arrays can provide a compact source of multipartite entanglement by embracing nonlinearity and coupling. We report our theoretical results on generation multimode continuous-variable (CV) entanglement in realistic nonlinear waveguide arrays. In our investigations we consider two type of nonlinear interactions : second harmonic generation (SHG) when the waveguides are pumped by modes oscillating at $\omega$ (fundamentals), and parametric downconversion (spontaneous and stimulated) when pumping at $2\omega$ (harmonics). In our analysis we suppose that the fundamental modes only arecoupled.

We start with the simplest case of two coupled waveguides. We show that for stimulated downconversion (optical parametric amplification) in the depletion regime, the harmonic fields become entangled although they remain independently guided in each waveguide [2]-[4]. Furthermore, under certain conditions, the harmonics exhibit two-color quadripartite entanglement with the fundamental modes, entangled by simultaneous coupling and downconversion. We also discuss here the possibility of producing multipartite entanglement in $\chi^{(2)}$ nonlinear waveguide arrays with large number of waveguides. Indeed, we show that arrays with an odd number $N$ of waveguides in the SHG regime pumped in a particular configuration of fundamental modes (zero supermode) support multipartite entanglement of $(N+1)/2$ fundamental modes [5]. Our strategy is scalable, robust to optical losses and does not rely on specific values of nonlinearity and coupling, which makes it very easy to implement with current fabrication technology using periodically poled Lithium Niobate waveguides. In our theoretical investigations, we also tackle the crucial limitation of $\chi^{(2)}$ nonlinear waveguide arrays : although each waveguide is wavevector quasi-phase matched ($\Delta\beta$-QPM) for the second order nonlinear interaction, the coupling between waveguides introduces an additional phase mismatch that limits the nonlinear conversion and strongly constrains the efficiency of entanglement generation. We introduce the coupling-QPM (C-QPM) as the QPM of selected supermodes (eigenmodes) of the array through suitable tailoring of the effective nonlinearity at a set super-period [6]. This technique can be combined with the usual $\Delta\beta$-QPM to achieve a continuous growth of the nonlinear interaction for the eigenmodes, yielding strong entanglement between the individual elements which make up these eigenmodes.

If time or space permits, we can introduce a general framework for multipartite entanglement in the spontaneous parametric downconversion regime and on-demand production of CV cluster states through pump engineering and measurement-basis reconfigurability.

[1] F. Lenzini, J. Janousek, O. Thearle, M. Villa, B. Haylock, S. Kasture, L. Cui, H.-P. Phan, D.V. Dao, H. Yonezawa, P.K. Lam, E.H. Huntington, M. Lobino. Integrated photonic platform for quantum information with continuous variables. Science Advances 4 (12), eaat9331 (2018).

[2] D. Barral, N. Belabas, L.M. Procopio, V. D'Auria, S. Tanzilli, K. Bencheikh, J.A. Levenson. Continuous-variables entanglement of two bright states that never interacted. Phys. Rev. A 96, 053822 (2017).

[3] D. Barral, K. Bencheikh, V. D'Auria, S. Tanzilli, N. Belabas, J.A. Levenson. Minimum resources for versatile continuous-variable entanglement in integrated nonlinear waveguides. Phys. Rev. A 98, 023857 (2018).

[4] D. Barral, K. Bencheikh, N. Belabas and J.A. Levenson. Symmetry-based analytical solutions to the $\chi^{(2)}$ nonlinear directional coupler. Phys. Rev. E 99, 042211 (2019).

[5] D. Barral, K. Bencheikh, N. Belabas and J.A. Levenson. Zero supermode-based multipartite entanglement in $\chi^{(2)}$ nonlinear waveguide arrays. Phys. Rev. A 99, 051801 (**R**) (2019).

[6] D. Barral, N. Belabas, K. Bencheikh, J.A. Levenson. Coupling quasi-phase matching : entanglement buildup in $\chi^{(2)}$ nonlinear waveguide arrays. Phys. Rev. A 100, 013824 (2019).

* david.barral@c2n.upsaclay.fr

# Complex entangled networks : optimization and manipulation via linear optics operations

Francesca Sansavini, and Valentina Parigi
*Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-PSL Research University, Collège de France ; CC74 4 Place Jussieu, 75252 Paris, France*

Multimode entangled states are essential tools which can be exploited both as a resource for measurement based ("one way") quantum computing (MBQC) and for multiparty quantum communication protocols. In our framework, we deal with a particular class of Continuous Variables (CV) multipartite entangled states, known as *cluster states*. They can be represented as networks, where each node denotes a mode of the electromagnetic field and each link denotes an entanglement link between quadratures of said modes.

The Quantum Optics group at Laboratoire Kastler Brossel implements cluster states via parametric processes pumped by optical frequency combs. This generates multimode squeezed resources that can be shaped into a network when subjected to linear optical manipulations, experimentally implemented via mode-dependent measurements. The main advantage of this implementation is that we can easily build the networks and reconfigure their shape, according to the task we want to perform [1, 2].

Here we consider the implementation of CV cluster states with complex shape, mimicking the ones of real-world networks. In particular, we consider their implementation in a realistic scenario, where we are provided with a certain amount of finitely squeezed modes, resulting in an imperfect resource. It is thus important to optimize given characteristics of these approximate cluster states to minimize the noise resulting in the implementation of a given QIP (Quantum Information Processing protocol) using an imperfect resource.

We implemented an analytical procedure for the generation of entangled complex networks, their optimization and their manipulation via global linear optics operations, focusing on the role played by topology. We also developed a numerical procedure, based on an evolutionary algorithm, for manipulating entanglement connections via local linear optics operations. The goal is the generation of a quantum channel between two arbitrary parties - not connected in the initial network - for the implementation of quantum communication protocols.

[1] J. Roslund, R. M. de Araújo, S. Jiang, C. Fabre and N. Treps, "Wavelength-multiplexed quantum networks with ultrafast frequency combs", Nature Photonics **8**, 109-112 (2014).

[2] Y. Cai, J. Roslund, G. Ferrini, F. Arzani, X. Xu, C. Fabre and N. Treps , "Multimode entanglement in reconfigurable graph states using optical frequency combs", Nature Communications **8**, 15645 (2017).

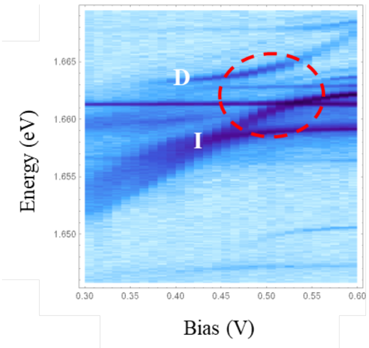
# Quantum Dot Molecules for on-chip quantum communications

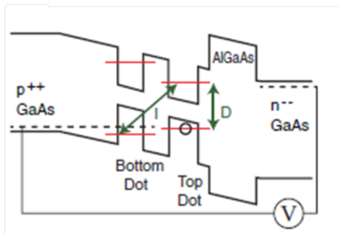
Savvas Germanis[1], Richard Hostein[1], Paola Atkinson[1], Benoit Eble[1] and Valia Voliotis[1]*
[1]*Sorbonne Université, CNRS,*
*Institut des Nanosciences de Paris, 75005 Paris France*

The discrete density of states of semiconductor Quantum Dots (QDs) and their easy integration into conventional semiconductor device structures make them attractive for applications in quantum communication networks. Here we present preliminary results on vertically stacked QDs separated by a barrier as a new system for addressing and manipulating spin qubits. The QDs of such pairs are coupled via coherent tunneling through the barrier leading to the formation of states with delocalized wavefunctions like in molecules. The ability to create hybridized states yields a large variety of available states with mixed spin character equivalent to $\Lambda$ systems that can be optically addressed. Moreover non-destructive read-out can be achieved by using different excited states [**?** ]. Taking advantage of "indirect" transitions involving electrons and holes located in separate QDs, it becomes also possible to tune the transitions easily into resonance with an optical cavity mode, due to the large energy shift with an extrernal applied bias.

GaAs/AlAs QDs samples are processed in a Schottky diode structure and the coupling between the vertically stacked QDs is achieved by applying an external electric field along the growth axis. Thanks to the different size of QDs the emission energies are well separated by almost 25 meV and coupling can be observed closer to the lower energy QD's emission range. Molecular states for electron are formed as we sweep the electric field and are evidenced by the observation of an anticrossing between indirect and direct transitions. The figure represents a plot of the lower energy QD emission as a function of the applied field. The direct and indirect transitions are labelled by D and I respectively. The field-effect device is also schematically represented.

The next step is to realize a charged-control device making possible hole spin manipulation. Hole spin in a QD molecule has many advantages since it is less sensitive to hyperfine interaction [**?** ] and spin mixing for holes can be larger than for electrons, enhancing the fidelity of the optical driven qubit rotation. Thus, QD molecules have great potential as storage units for spin qubits with long coherence times and quantum gates necessary for quantum computation protocols.




[1] S. Economou, *et al*, Phys. Rev. **B**, 86, 085319 (2012).

[2] B. Eble, *et al*, Phys. Rev. Lett. **102**, 146601 (2009).

* savvas.germanis@insp.jussieu.fr

# GDR IQFA - 10th Colloquium

Federico Centrone[1,2], Eleni Diamanti[1], Iordanis Kerenidis[2]
[1]*LIP6, UPMC, Sorbonne Université, Paris*
[2]*IRIF, Paris Diderot, Université Sorbonne Paris Cité, Paris*

## QUANTUM ADVANTAGE WITH COHERENT STATES

The quest for an evidence of a quantum device outperforming the best existing classical computer in time resources for some specific computational task, the so-called Quantum Advantage, is a long-standing goal in the field of Quantum Information. The recent leakage by NASA and Google of an article showing the performance of their 53 qubits superconducting quantum processor in sampling randoms quantum circuits is the first experimental proof of such advantage and, although its practical applications are limited, it represents a milestone for the research in this area.

Recently, we could observe experimental evidence for a quantum advantage in the verification of 3-SAT problems through the implementation of a Quantum Merlin Arthur (QMA) instance in a rather simple optical setup. QMA is a Quantum Interactive Proof system in which a computationally unbounded but untrusted *prover*, Merlin, wants to convince Arthur, the *verifier*, that he can solve a given satisfiability problem, by sending quantum proofs. Even though the information received by the prover is bounded, if a solution exists he would accept the proof in polynomial time with high probability (*completeness*), otherwise he would reject, still in polynomial time and with high probability (*soundness*). In the classical case, if Arthur receives only $K$ bits out of the $N$ of the complete solution, he would need exponential time in the number of missing bits $N - K$ to verify the problem, whereas our quantum protocol takes linear time in the input size $N$.

By encoding the information in weak coherent pulses and allowing Merlin's quantum proofs to live in an infinite dimensional Hilbert space, we could generalize this complexity class to a regime that was never explored before, achieving results that are not possible in the discrete variable case. These results allow an experimental implementation that requires only a standard laser source, a number of passive optical elements independent of the input size of the problem and single photon detectors, thus technologies available in almost any optical laboratory. The protocol, taking into account the experimental imperfections, can verify a NP-complete problem of arbitrary input size with high probability of success in a fraction of a second, whereas the classical analog to achieve the same level of confidence would need thousands of years.

## A QUANTUM PROTOCOL FOR DEMOCRACY

Quantum based technology has the potentiality to revolutionize society in several aspects. Some functionalities, that result strictly prohibitive in a classical framework, often become efficient and secure in the context of quantum information. Nonetheless, there are some highly desirable utilities that do not seem to find their realization neither in the classical nor in the quantum realms. One of these is electronic voting, which is any protocol capable of performing up to large scale elections through a distributed network, such as the internet, in a secure and verified way. If, on the one hand, this functionality would simplify the accessibility to elections and increment the public participation to democracy, on the other hand the adoption of a public network increases the possible frauds one can perform to manipulate the results or violate the privacy.

All the existing voting platform have been proved to be insecure to guarantee privacy and all the proposed theoretical protocols, both classical and quantum, are either very impractical or unreliable in some aspects. Establishing a formal definition of the notions of security in the context of e-voting and exploiting some results for multipartite entangled state verification, we could devise a quantum protocol allowing $N$ voters to perform an election in efficient time, without relying on any election authority, with an arbitrary number of dishonest agents and with information-theoretic security for the properties of *correctness*, *privacy*, *verifiability* and *receipt freedom*. This protocol requires the manipulation of a N-particles GHZ state and can be implemented in our laboratory for a small number of voters.

# Random coding for sharing bosonic quantum secrets

Francesco Arzani[1,2], Giulia Ferrini[3], Frédéric Grosshans[2], and Damian Markham[2*]
[1]*Université de Lorraine, Centre National de la Recherche Scientifique, Inria, LORIA, F 54000 Nancy, France*
[2]*Sorbonne Université, Centre National de la Recherche Scientifique,*
*Laboratoire d'informatique de Paris 6, F-75005 Paris, France*
[3]*Department of Microtechnology and Nanoscience (MC2),*
*Chalmers University of Technology, SE-412 96 Gothenburg, Sweden*

***Introduction*** Quantum systems are notoriously fragile : small losses or weak interactions with the outside world usually destroy quantum coherence. Since quantum information cannot be copied, any leakage of information leads to its destruction in the original system. To fully retrieve it, one usually needs full control over the environment. The loss of coherence is at the heart of quantum information, whether we want to fight it or impose it to an adversary, but it plays an important role in a broader area of physics, including thermodynamics, quantum control, and black hole physics [1]. Among the strategies devised to try and overcome this fragility are quantum error correcting (QEC) codes and quantum secret sharing (QSS) schemes. Secret sharing is an important primitive for mutlipartite cryptography, used for example in electronic voting, byzantine agreement and secure multiparty computation. The original classical protocol was introduced by Shamir in the seventies [2], and the first quantum versions appeared in a series of works about twenty years ago [3, 4]. In QSS schemes, a dealer delocalizes the information between several players, so that only authorized subsets of them (access parties) can fully reconstruct the original information without the shares of the other players. Unathorized sets on the other hand get in principle no information about the secret. It was shown for qubits that QSS schemes are equivalent to erasure correcting codes [5], protecting against loss of part of the system (the complement of any authorized set). As most ECC codes, QSS schemes are highly structured. However, random codes exist that have been proven to optimally protect the state of a set of qubits from erasure errors [6]. Their randomness makes them a natural model in a variety of physical scenarios where information is lost. Alternative to qubits, information can be encoded in the state of infinite dimensional quantum systems, known as continuousvariable (CV) systems. The name comes from the existence of observables with continuous spectra, such as position and momentum, here referred to as quadratures, as is customary in quantum optics. CV systems are of great practical importance in quantum technologies : the possibility to experimentally generate entanglement in a deterministic fashion makes them interesting candidates for the realization of quantum communication and computation protocols. Several CV generalizations of QSS [7] and erasure-correcting codes [8] have been proposed, and some have been experimentally demonstrated [9]. Each of these schemes, however, requires encoding the secret in carefully chosen states. No CV random code has been proposed to date. This gap poses serious limitations to the experimental realization of CV-QSS. For example, unless the experimental setup is specifically tailored for the task, CV-QSS could not be carried out, or experimental imperfections might hinder its implementation.

***Results*** We fill this gap [10] by introducing a form of random coding for CV. Namely, we show that QSS can be implemented in bosonic systems mixing a secret state with squeezed states, the workhorse of CV quantum information, through almost any energy preserving transformation. The latter correspond to passive interferometers in the optical setting. We show that for almost any passive transformation there exists a Gaussian decoding scheme, that each authorized set can construct efficiently, such that the secret can be recovered to arbitrary precision, provided the initial squeezing is high enough. We show that in the optical case, decoding can be achieved by interferometry, homodyne detection and a of single mode squeezers independent of the number of players. We stress that our results follow from simple linear algebra and general considerations on the number of modes. Our approach also generalizes earlier proposals by allowing the secret to be an arbitrary multimode state, as long as enough players are considered. These results have immediate experimental and technological applications. Indeed, they imply that almost any experimental setup involving squeezed states can beused for QSS. Moreover, small deviations of the setup from a theoretical target one are not important, as long as they can be characterized. This opens the possibility to share resource states securely over a network of CV systems with arbitrarily distributed entanglement links, which may pave the way to server-client architectures for CV quantum computation.

* fra.arzani@gmail.com

[1] P. Hayden and J. Preskill, JHEP 2007, 120 (2007).
[2] A. Shamir, Commun. ACM 22, 612 (1979).
[3] M. Hillery, V. Bužek, and A. Berthiaume, PRA 59, 1829 (1999).
[4] R. Cleve, D. Gottesman, and H.-K. Lo, PRL 83, 648 (1999).
[5] D. Gottesman, Phys. Rev. A 61, 042311 (2000).
[6] P. Hayden, P. W. Shor, and A. Winter, Open Systems and Information Dynamics 15, 71 (2008).
[7] T. Tyc and B. C. Sanders, PRA 65, 042310 (2002).
[8] J. Niset, U. L. Andersen, and N. J. Cerf, PRL 101, 130503 (2008).
[9] A. M. Lance, T. Symul, W. P. Bowen, B. C. Sanders, and P. K. Lam, PRL 92, 177903 (2004).
[10] **F. Arzani, G. Ferrini, F. Grosshans, D. Markham, PRA 100, 022303 (2019).**

# CW generation of single photons pairs by Spontaneous Four Wave Mixing in silica nanofibers

Philippe Delaye, Tao Liu, Maha Bouhadida, Sylvie Lebrun
Laboratoire Charles Fabry, Institut d'Optique Graduate School, CNRS, 2 Av. Augustin Fresnel 91127 Palaiseau

Nanofibers obtained by elongation of standard optical fibers allow the realization of functionalized in-line fiber components for various applications, from sensors to signal processing components based on nonlinear mechanisms. Among these last applications, nanofibers are particularly interesting to realize single photon pairs sources based on spontaneous four wave mixing. We will present encouraging preliminary results of generation of pairs of photons in the Continuous Wave (CW) regime with measured Coincidence to Accidental Ratio (CAR) greater that 1000.

The nanofibers present several advantages for nonlinear optics, their diameter can be reduced to sub-micrometer dimensions, what lead to a strong reduction of the nonlinear effective area and thus a high nonlinear efficiency. They can be drawn to large length up to several centimeters, together with optimized tapers that allow almost loss-free injection of the beams issued from the access fiber. This allows to design high efficiency nonlinear devices with reduces length. Another great advantage of these nanofibers is the possibility to adjust the Zero Dispersion Wavelengths and thus the phase matching characteristics in four wave mixing mechanisms. For example, using a fiber with 850nm diameter, it is possible to realize spontaneous four wave mixing phase matching with a Ti:Sapphire pump around 900nm to emit two time-correlated photons in the telecom band and the visible.

The nonlinear properties of the drawn fiber are characterized using self-phase modulation spectrum broadening of a picosecond pulsed pump. Nonlinear phase shift, up to $2\pi$ can be reached with moderate average pump power in the 10mW range, largely sufficient to observe single photon pair emission. This emission is characterized using a Stimulated Emission Tomography [1] experimental set-up, we have developed for this occasion. This set-up allows to characterize easily and rapidly the Joint Spectral Intensity (JSI) [2] of different drawn nanofibers. This first characterization allows to validate the potential of the nanofibers and identify precisely the wavelength of the emitted photons, before using the single photon detectors to measure the correlated pairs.

Photons pairs were easily observed in the pulsed regime as expected from the nonlinear characterization results. We could particularly measure that the Raman noise contamination was reduced thanks to the large wavelength separation of the emitted photons. A small linear contribution due to multi-phonon Raman scattering in silica material was nevertheless still present on the idler side, but estimated to be sufficiently small, so that it cannot prevent observation of single photons in the CW regime.

Using the Ti:Sapphire laser in the CW regime, we could measure the JSI in the Stimulated Emission Tomography experiment, what confirms the potential of the nanofibers. Finally, we could observe pair emission with high signal to noise ratio, typically greater than several hundred, with the higher up-to-date measured value in a fiber geometry, with a CAR of 1200, in one of the drawn nanofibers.

These first preliminary results are very encouraging. High efficiencies are obtained with high signal to noise ratio despite the fact that the used nanofibers are still not optimized. Some points are still to improved and will be the objectives of our futures works, the main one is the problem of the reproducibility and non-uniformity of the nanofibers diameter, that has been estimated of the order of ±1 to ±10nm on the nanofibers we have used in these preliminary experiments. This parameter can be controlled by optimizing the drawing condition. This optimization will be facilitated by use of the Stimulated Emission Tomography that allows to characterize easily and very rapidly the emission spectrum, and to correlate it to the drawing parameters.

This work had been performed in the frame of the ANR FUNFILM project.

[1] M. Liscidini, J. Sipe, "Stimulated emission tomography," Phys. Rev. Lett. **111**, 193602 (2013).
[2] M. Cordier, A. Orieux, B. Debord, F. Gérôme, A. Gorse, M. Chafer, E. Diamanti, P. Delaye, F. Benabid, I. Zaquine, "Active engineering of four-wave mixing spectral correlations in multiband hollow-core fibers " Opt. Expr. 27, 9803 (2019).

# Distributing Graph States Over Arbitrary Quantum Networks

Clément Meignant[1], Damian Markham[1], and Frédéric Grosshans[1,2*]
[1]*Sorbonne Université, CNRS, LIP6, F-75005 Paris, France*
[2]*Laboratoire Aimé Cotton, CNRS, Univ. Paris-Sud, ENS Cachan, Univ. Paris-Saclay, 91405 Orsay Cedex*

Multipartite entangled states are great resources for quantum networks. In this work [1] we study the distribution, or routing, of entangled states over fixed, but arbitrary, physical networks. Our simplified model represents each use of a quantum channel as the sharing of a Bell pair ; local operations and classical communications are considered to be free. We introduce two protocols to distribute respectively Greenberger–Horne–Zeilinger (GHZ) states (al illustrated below) and arbitrary graph states over arbitrary quantum networks. The GHZ states distribution protocol takes a single step and is optimal in terms of the number of Bell pairs used ; the graph state distribution protocol uses at most twice as many Bell pairs and steps than the optimal routing protocol for the worst case scenario.

FIGURE 1. Our elementary operation to expand a graph state over a network, star-expansion, using **a)** local $CZ$ operations ; **b)** local complementation ; **c)** either remove a useless qubit by $Z$-measuring it ; **e)** or keep it and apply local $CZ$ gates ; **f)** $Y$-measurements

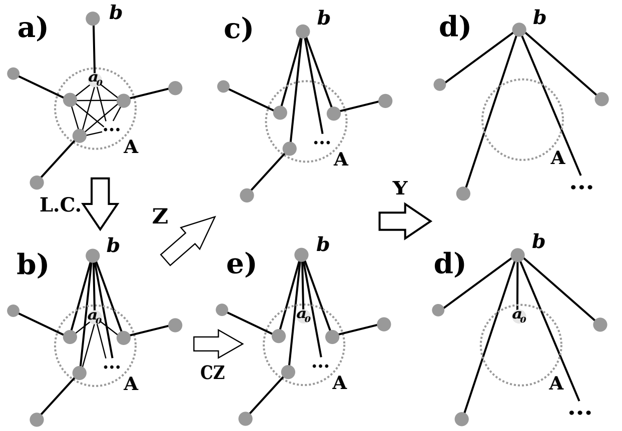
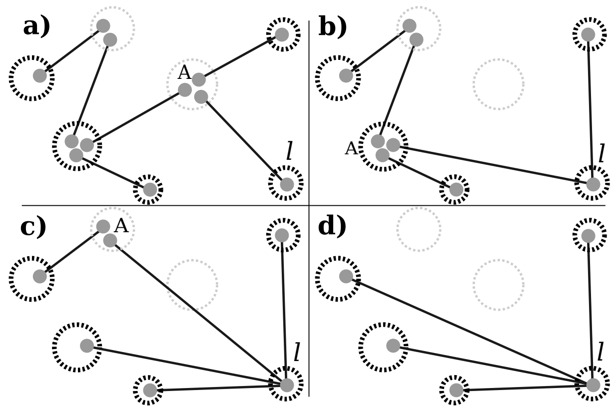



FIGURE 2. Distribution of a GHZ state. We distribute the star graph over the nodes represented by black-dotted circles. To explore the tree, we arbitrarily choose a non-leaf neighbour of $\ell$ and apply star expansion on that node $A$ (taking $\ell$ as Bob). We repeat this until we arrive at the desired star over $W$.




We acknowledge support of the ANR through the ANR-17-CE24-0035 VanQute project and from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820445 QIA project.

[1] C. Meignant, D. Markham, and F. Grosshans, (2018), arXiv :1811.05445.

* frederic.grosshans@lip6.fr

# Hong-Ou-Mandel Experiment with Imperfect Single-Photon Sources

S. E. Thomas[1,*], H. Ollivier[1], I. Maillette de Buy Wenniger[1], J. C. Loredo[1], N. Somaschi[1], A. Harouri[1], A. Lemaitre[1], I. Sagnes[1], L. Lanco[1,2], O. Krebs[1], C. Anton[1], and P. Senellart[1]
[1]*Centre for Nanosciences and Nanotechnology, CNRS,*
*Université Paris-Saclay, UMR 9001,*
*10 Boulevard Thomas Gobert, 91120, Palaiseau, France*
[2] *Université Paris Diderot - Paris 7,*
*75205 Paris CEDEX 13, France*
[*] *sarah.thomas@c2n.upsaclay.fr*

The Hong-Ou-Mandel (HOM) effect is a cornerstone of quantum optics. This experiment measures the interference of photons at a beam splitter, and the degree of interference depends on the photons' distinguishability [1]. This effect is a critical component of optical circuits in photonic quantum information processing. Furthermore, the degree of bunching is a commonly used metric to quantify the degree of indistinguishability, or the wavefunction overlap, $M$, between two photonic wavepackets.

Here we investigate how HOM interference changes with practical, imperfect single photon sources. The photonic state arriving at each input of the beam splitter can contain a small two-photon component which is known to affect the measured HOM interference. However, the origin of the second photon, which varies depending on the type of single-photon source, can have a distinct effect on the resultant interference.

We quantify the probability of having two photons in the input state by measuring the second-order autocorrelation, or $g^{(2)}$. The mean photon overlap between these two photons is given by $M'$. We develop a theoretical model which predicts that the relationship between $g^{(2)}$ and the number of measured coincidences, $P_{11}$, scales as $P_{11} = \frac{1}{2}\left(1 - M + g^{(2)}(0)(1 + M - MM')\right)$. Therefore, to quantify indistinguishability, $M$, it is vital to know the origin and distinguishability ($M'$) of any additional photons in the input state.

To test this theory we experimentally vary the size of the two-photon component for the two limiting cases : when the additional photon is fully *indistinguishable* or fully *distinguishable* from the dominant, single-photon component, and the results are in good agreement with our model.

We then investigate two realistic, imperfect single-photon sources based on quantum dots. For a neutral exciton quantum dot, the dominant two-photon component originates from imperfect suppression of the resonant excitation laser. We confirm this by introducing additional spectral filtering of the laser and see a significant decrease in the measured $g^{(2)}$. We deliberately decrease the polarisation suppression of the laser to increase the $g^{(2)}$ of this source, and measure the impact on HOM interference. A fit with our model predicts $M' \approx 0.3$, since there is low spectral overlap between the laser and the emitted single photon from the quantum dot.

For the case of a charged exciton based source, the predominant origin of two-photon emission is re-excitation during the laser pulse duration. This is confirmed by increasing the pulse length of the excitation pulse and seeing an increase in $g^{(2)}$, in contrast to the neutral exciton where $g^{(2)}$ is independent of pulse length. The second emitted photon for the charged exciton is due to stimulated emission during the laser pulse and therefore the spectrum of this photon matches that of the laser, and again has a low wavepacket overlap with the predominant single photon wavepacket. For both cases, the correction to the measured coincidences, $P_{11}$, is the same since the additional photon has, or inherits, the spectrum of the laser, even though the physical mechanisms are different.

This model allows us to find a simple correction factor to account for two-photon components in HOM interference. By knowing the origin of two-photon emission for different imperfect single-photon sources, we can predict the impact on the measured visibility of HOM interference and deduce the true wavepacket overlap between subsequent photons emitted from these sources.

[1] C. K. Hong, Z. Y. Ou and L. Mandel, "Measurement of subpicosecond time intervals between two photons by interference". Phys. Rev. Lett. **59** 2044–2046 (1987)

# Generation and manipulation of high-dimensional frequency states on an AlGaAs chip

G. Maltese[1], F. Appas[1], M. Amanti[1], A. Lemaître[2], F. Baboux[1], and S. Ducci[1]

[1]Laboratoire Matériaux et Phénomènes Quantiques, Université Paris Diderot, Sorbonne Paris Cité, CNRS-UMR 7162, 75205 Paris Cedex 13, France
[2]Centre de Nanosciences et de Nanotechnologies, CNRS/Université Paris Sud, UMR 9001, France

12 février 2019

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

In this work we present an AlGaAs waveguide emitting entangled photon pairs displaying a frequency comb-like spectrum through spontaneous parametric down conversion. We demonstrate, using a Hong-Ou-Mandel setup, that the fine tuning of the pump frequency controls the symmetry of the wavefunction to obtain either bosonic or fermionic behavior.

Our source consists of an AlGaAs non-linear waveguide that emits two-photon states in the telecom range at room temperature with a generation rate of 2,37 MHz and a SNR up to $5\text{x}10^4$. The dispersion properties of the devices, combined to energy and momentum conservation, lead to the generation of photon pairs which are entangled in polarization and frequency. Moreover, due to the reflectivity of its facets, the waveguide acts as a Fabry-Perot cavity and the two-photon spectrum takes the form of a frequency comb spanning several tens of nanometers. The measured biphoton joint spectral intensity in Fig. a) presents a strong frequency anti-correlation with peaks spaced of around 20 GHz.

Furthermore, we use Hong-Ou-Mandel (HOM) two-photon interference as a proof for quantum state manipulation. The central HOM dip in Fig. b) has a visibility of 85% and a width corresponding to a biphoton bandwidth of around 150 nm ; this excludes the generation of a frequency-correlated classical mixed state or of a quantum-classical mixed state. Fine tuning of the pump frequency switches the HOM interference signal form bunching c) to anti-bunching d) [3]. These results demonstrate the ability of our chip to generate and manipulate high-dimensional entangled states and open the way to its utilization in quantum information protocols.

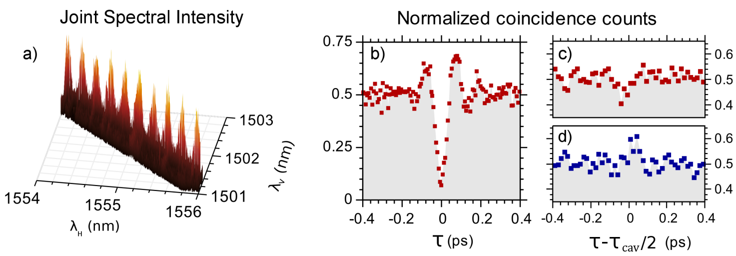



FIGURE 1 – Characterization of the biphoton state emitted by our device : measurements of the Joint Spectral Intensity (a), HOM interference at zero delay (b) and for a time delay corresponding to the half of the cavity roundtrip for two different values of the pump beam frequency (c,d)

## Références


[1] F. Boitier et al. “Electrically injected photon-pair source at room temperature”, Phys. Rev. Lett. 112, 183901 (2014).

[2] M. Kues et al. “On-chip generation of high-dimensional entangled quantum states and their coherent control” Nature 546, 622 (2017).

[3] G. Maltese et al. in preparation.

# Fibered tunable heralded single photon source at telecom wavelength

**M. Cordier[1], F. Benabid[2] P. Delaye[3] and I. Zaquine[1]**

*1. Laboratoire de Traitement et Communication de l'Information, Télécom Paris, Institut Polytechnique de Paris, 91120 Palaiseau France*

*2. GPPMM Group, XLIM Research Institute, CNRS UMR 7252, Univ Limoges, Limoges, France*

*3. Laboratoire Charles Fabry, Institut d'Optique Graduate School, CNRS, Univ Paris-Saclay, 91127 Palaiseau France*

Gas-filled hollow-core photonic crystal fibers provide a versatile Raman-free platform for photon pair generation through spontaneous four wave mixing that can be very useful for the future quantum communication networks. The inhibited-coupling HCPCF (see Fig.1a) filled with xenon, was designed to operate at wavelengths that are convenient for heralded single photon sources; the idler lies in the telecom wavelength range (~ 1545 nm), while the signal wavelength is in the range of atomic transitions and Silicon single photon detectors (~ 778 nm).

The source combines three important features: (1) Raman-free generation thanks to the use of a noble gas and to a minute overlap with silica within the hollow-core [1]; (2) strong efficiency nonlinear medium and (3) a high versatility in the phase-matching conditions thanks to the fiber microstructuration and gas pressure tunability.

We have shown that the spectral correlation of these pairs can be engineered to obtain entangled or separable states [2], the latter being the backbone in heralded single photon sources. The amount of spectral correlations is well-described by the shape of the Joint Spectral amplitude function (JSA), which mostly depends on the relative group velocity relation between the pump, signal and idler photons within the source medium [3]. We show how the multiband dispersion profile of such medium allows to tailor phase- and group velocity relations and possibly at any given wavelength from the UV to infrared [3]. We demonstrate experimentally an active control over the generated photon spectral-correlation that allows spectrally entangled and factorable states to be obtained within the same device (examples in Fig.1.c). More specifically, a gallery of different JSI, including exotic shape, is measured by tuning various parameters: gas pressure, pump spectral FWHM, spectral chirp and pump spectral envelope. Such a versatile photon-pair source can target both applications requiring factorable (heralded single photon) and correlated states (spectral entanglement or QKD) and paves the way to spectro-temporal mode encoding [4].

The photon-pair state is generated over an unprecedented tunable frequency-range that span well over tens if THz. Thanks to the high coincidence to accidental ratio (2700) we have obtained, we demonstrate a fibered heralded single photon source with a g(2)(0) as low as 0.002 and a heralding efficiency of 27%.

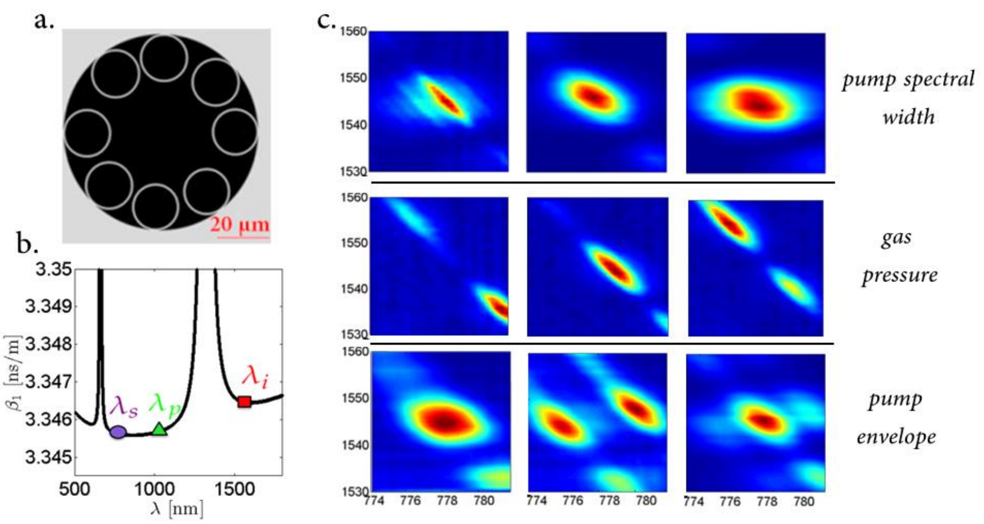



**Fig. 1 a.** Fiber cross-section measured with an optical microscope. **b.** Simulated inverse-group velocity exhibiting a multiband profile. **c.** Measured joint-spectral intensity (JSI) of the source for different experimental parameters; The JSI are obtained using the stimulated emission tomography technique.

**References**

[1] B. Debord, et al. "Ultralow transmission loss in inhibited-coupling guiding hollow fibers. " Optica 4.2 (2017): 209-217.

[2] Cordier, Martin, et al. "Active engineering of four-wave mixing spectral correlations in multiband hollow-core fibers." Optics express 27.7 (2019): 9803-9814.

[3] W. P. Grice et al., "Eliminating frequency and space-time correlations in multiphoton states," PRA 64, 063815 (2001)

[4] C. Silberhorn et al., "Photon temporal modes: a complete framework for quantum information science, " PRX 5(4), 2015

# Quantum Sensing & Metrology (QMET)

# Entanglement-based quantum holography

Hugo Defienne*, Bienvenu Ndagano, Ashely Lyons and Daniele Faccio
*School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK*

Quantum characteristics have made quantum light a key enabler for emerging new imaging technologies [1]. However, quantum imaging systems have often mimetic relatives that use classical state to realize the essential of their performance. In this respect, entanglement - probably the most unique feature of quantum mechanics - is in general not used [2]. Here we introduced and experimentally demonstrate a holographic imaging approach that is genuinely based on quantum entanglement. In our experiment, Alice encrypts an image in the phase component of space-polarisation hyperentangled photons [3] using a spatial light modulator. The image is next reconstructed by Bob using a full-field quantum holographic technique based on intensity correlation measurements performed with an EMCCD camera [4]. We demonstrate that our approach requires the presence of polarisation entanglement between photons to work. Moreover, we show that entanglement-encrypted phase images propagate without disturbance through dynamic phase disorder and can be retrieved in the presence stray light, two factors that would respectively disrupt and inhibit a phase reconstruction process in classical holography. Our entanglement-based quantum holographic scheme is a prototype in quantum information - an image can be encrypted and decrypted using photonic entanglement as an information support. Its application ranges beyond the field of imaging, paving the way towards the development of quantum image encryption schemes for security applications [5] and high-dimensional quantum communication protocols in turbulent environments [6].

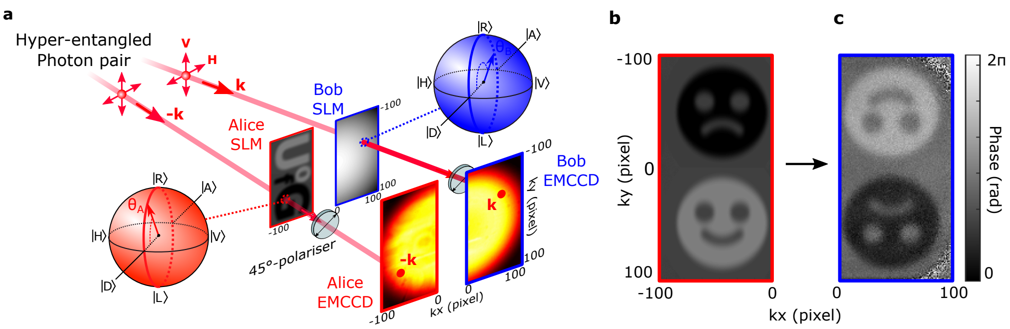



FIGURE 1: **Schematic of the quantum holographic process. a**, Spatial-polarisation hyperentangled photon pairs propagate through two spatial light modulators (Alice SLM and Bob SLM) and are detected by two EMCCD cameras (Alice EMCCD and Bob EMCCD). SLMs allow Alice and Bob to control phase values $\theta_A$ and $\theta_B$ of the horizontal polarisation of incoming photons at any pixel, which corresponds to rotating their polarisation along a meridian of the Poincarre sphere. Two polarisers oriented at 45 degrees are inserted between SLMs and cameras. **b**, Phase image displayed on Alice SLM. **c** Phase image reconstructed by Bob by performing intensity correlation measurement between pixels **k** and their symmetric **-k** on Alice sensor using the EMCCD cameras.

[1] P-A. Moreau, B. Toninelli, T. Gregory, M.J. Padgett, "Imaging with quantum states of light", Nat. Rev. Phys. **1**, 367-380 (2019).
[2] A.F. Abouraddy, B.E. Saleh, A.V. Sergienko, M.C. Teich."Role of entanglement in two-photon imaging". Phys. Rev. Lett., **87**(12), 123602 (2001).
[3] J. T. Barreiro, N. K. Langford, N. A. Peters, P. G Kwiat. "Generation of hyperentangled photon pairs". Phys. Rev. Lett., **95**(26), 260501 (2005).
[4] H. Defienne, M. Reichert, J.W. Fleischer. "General model of photon-pair detection with an image sensor". Phys. Rev. Lett., **120**(20), 203604 (2018).
[5] P. Refregier, B. Javidi. "Optical image encryption based on input plane and Fourier plane random encoding". Opt. Lett., **20**(7), 767-769 (1995).
[6] M. Malik, O.S. Magaña-Loaiza, R.W. Boyd "Quantum-secured imaging". App. Phys. Lett., **101**(24), 241103 (2012).

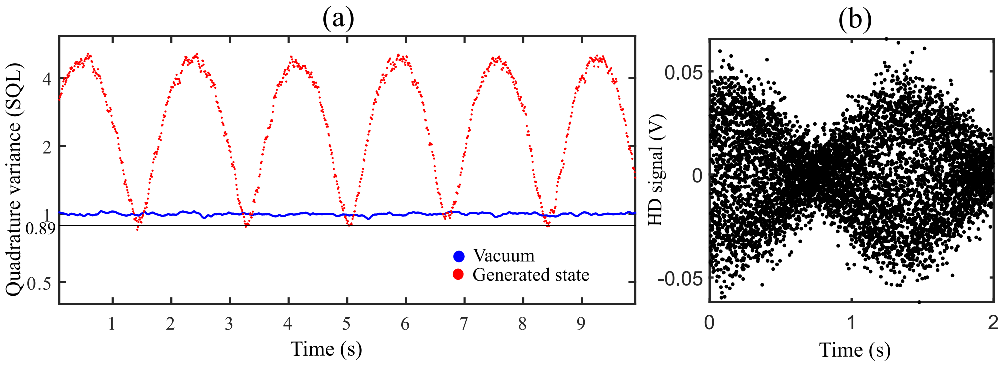
* Presenter email : hugo.defienne@glasgow.ac.uk

# Squeezed vacuum and squeezed single photons mixture generation by four-wave mixing

Pascal Neveu, Joseph Delpy, Etienne Brion, Fabien Bretenaker and Fabienne Goldfarb.*
*Laboratoire Aimé Cotton, CNRS - Université Paris Sud 11 - ENS Paris-Saclay, 91405 Orsay Cedex, France*

Phase Sensitive Amplifiers (PSA) have been a subject of broad interest in a variety of fields due to its unique noise properties [1]. It enables squeezing of a light field, which can be used as a basic brick for quantum information and telecommunication processings in the continuous variable domain [2]. Usually, such nonlinear processes are far-detuned from optical transitions to avoid losses from absorption. However, nonlinearities can be enhanced by resonantly exciting a transition while using coherent population trapping into a dark state to forbid its linear absorption. We have recently reported a strong and highly pure PSA using a resonant excitation of the D1 ($2^3S_1 \leftrightarrow 2^3P_1$) transition in metastable helium at room temperature [3, 4]. An amplification up to 9 dB could be achieved despite a low optical depth (about 4.5). This nonlinearity takes benefits from the transparent D1 transition and the far-detuned D2 ($2^3S_1 \leftrightarrow 2^3P_2$) transition.

In the present work, we report the quantum statistics properties of the output quantum state generated by the process. We observe squeezing of the variance of the output state of -2 dB below the standart quantum limit, after taking into account detection losses. More interestingly, the residual absorption by the D2 transition induces losses, but also redistributes the input state with spontaneously emitted photons into the mode of the squeezed vacuum. The state finally obtained is thus a highly nonclassical mixture of squeezed vacuum and squeezed photons. Although absorption is lossy, the associated redistribution of squeezed vacuum in a mixture with single photons is a nongaussian operation, which tends to generate nongaussian states without an explicit heralded detection technique.




**(a)** Quadratures variances are scanned as a function of time. -2 dB squeezing below the standart quantum limit is extracted, when detection losses are taken into account. **(b)** Direct measurement of the quadratures by the homodyne detection (HD) setup.

[1] G. S. Agarwal, "Quantum Optics", (Cambridge, 2013).
[2] Y-S Ra, A. Dufour, M. Walschaers, C. Jacquard, T. Michel, C. Fabre and Nicolas Treps, "Non-Gaussian quantum states of a multimode light field", arXiv 1901.10939 (2019).
[3] J. Lugani, C. Banerjee, M.-A. Maynard, P. Neveu, W. Xie, R. Ghosh, F. Bretenaker, and F. Goldfarb, "Phase-Sensitive Amplification via Coherent Population Oscillations in Metastable Helium at Room Temperature", Opt. Lett. **41**, 4731-4734.
[4] P. Neveu, C. Banerjee, J. Lugani, F. Bretenaker, E. Brion and F. Goldfarb, "Phase Sensitive Amplification Enabled by Coherent Population Trapping, New J. Phys. **20** 083043 (2018).

* pascal.neveu@u-psud.fr

# Graph States as a Resource for Quantum Metrology

Nathan Shettell[1] and Damian Markham[1]
[1] *Laboratoire d'Informatique de Paris 6, CNRS,*
*Sorbonne Université, 4 place Jussieu, 75005 Paris, France*

The field of quantum metrology has been on the rise for the past few years, and has many applications such as spectroscopy, gravitational wave detection and other high precision measurements. In essence, quantum metrology uses quantum probes to measure physical quantities, and entanglement between probes allows us to achieve a precision superior to the classical analogue.

The maximum precision a quantum state can achieve is bounded by the Heisenberg limit. Unfortunately, quantum states which can achieve the Heisenberg limit can be very susceptible to noise, and it is a great challenge of the field to maintain quantum advantage in realistic conditions.

In our work [1] we investigate the practicality of graph states for quantum metrology. Graph states are a natural resources for many fields of quantum information, including quantum cryptography, quantum networks and quantum error correction. It is a natural question to determine whether we can include quantum metrology in this list.

We focus on the canonical case of quantum metrology - phase estimation. We show that there is a relationship between the topology of the graph state and the quantum Fisher information (QFI); the more pairs of vertices with identical neighbourhoods the higher the QFI. Using this as a baseline requirement, we construct a class of graph states which achieve a QFI of at least $n^{2-\log_n k}$, thus as $n \gg k$ the QFI approaches the Heisenberg limit.

Next, we explore the robustness of graph states subjected to independent and identically distributed (iid) dephasing and a small number of erasures. As expected, the QFI of a general graph $G$ subjected to noisy environments depend heavily on the shape of the graph. We see that general graphs retain a quantum advantage when the dephasing probability $p < 0.2$. Additionally, bundled cyclic graphs retain a quantum advantage after a small number of erasures. In comparison, the GHZ state becomes completely useless after a single erasure [2].

Lastly, we explore the necessary measurement to achieve a precision of $\Delta\theta^2 = 1/\mathcal{Q}$ with graph states. In phase estimation, this is done by measuring in the basis of the semi-logarithmic derivative. Typically, this is a highly entangled measurement or dependent on the unknown parameter [3]. We show that graph states can approximately achieve this precision by making single qubit measurements. This is done by measuring in a stabilizer basis consisting of entirely Pauli $Y$ and $Z$ operators. With this in mind, and all aforementioned properties, suggests that graph states are a useful resource for quantum metrology.

[1] N. Shettell, and D. Markham, "Graph States as a Resource for Quantum Metrology", arXiv preprint arXiv :1908.05047 (2019).
[2] G. Tóth, and I. Apellaniz, "Quantum metrology from a quantum information science perspective", Journal of Physics A : Mathematical and Theoretical, 47(42), 424006 (2014).
[3] G. Chiribella, G. M. ChD'Ariano, P. Perinotti, and M. F. Sacchi, "Covariant quantum measurements that maximize the likelihood", Physical Review A, 70(6), 062105 (2004).

# High sensitivity quantum-limited electron spin resonance

V. Ranjan[1,*] S. Probst[1], B. Albanese[1], E. Flurin[1], J. J. Pla[2], D. Vion[1], D. Esteve[1], J. J. L. Morton[3], and P. Bertet[1]
[1] *Quantronics group, SPEC, CEA, CNRS, Universite Paris-Saclay, CEA Saclay 91191 Gif-sur-Yvette Cedex, France*
[2] *School of Electrical Engineering and Telecommunications, University of New South Wales, Anzac Parade, Sydney, NSW 2052, Australia*
[3] *London Centre for Nanotechnology, University College London, London WC1H 0AH, United Kingdom*

In a conventional electron spin resonance (ESR) spectrometer based on the inductive detection method, the paramagnetic spins precess in an external magnetic field $B_0$ radiating weak microwave signals into a resonant cavity which are subsequently amplified and measured. Despite its widespread use, ESR spectroscopy has limited sensitivity, and large amounts of spins are necessary to accumulate sufficient signal. Most conventional ESR spectrometers operate at room temperature and employ three-dimensional cavities. At X-band, they require approximately $10^{13}$ spins to obtain sufficient signal in a single echo [1]. Enhancing this sensitivity to smaller spin ensembles and eventually the single spin limit is highly desirable.

Exploiting recent progress in circuit-quantum electrodynamics, we have combined high quality factor superconducting micro-resonators and noise-less Josephson Parametric Amplifiers to perform ESR spectroscopy at millikelvin temperatures, reaching a new regime where the sensitivity is limited by the quantum fluctuations of the microwave field. Quantum fluctuations of the field also affect directly the spin dynamics via Purcell effect : spin relaxation occurs dominantly by spontaneous emissions of microwave photons. Based on these principles [2-4], we first show an unprecedented measurement sensitivity of $\sim$ 10 spins/$\sqrt{\mathrm{Hz}}$ for unit SNR in an inductive-detection ESR with an ensemble of Bismuth donors in Silicon [5]. This high sensitivity enables us to characterize the coherence properties of an ensemble of donors in close proximity ($\sim 50 - 100$ nm) to the silicon surface, with spatial resolution. We identify surface magnetic and electric noise as the main decoherence sources in our device. At the so-called "clock transition", the coherence time approaches 1s, which is the longest reported for an electron spin close to a surface [6].

[1] A. Schweiger and G. Jeschke, Principles of pulse electron paramagnetic resonance (Oxford University Press, 2001).
[2] P. Haikka, Y. Kubo, A. Bienfait, P. Bertet, K. Moelmer, Phys. Rev. A 95, 022306 (2017).
[3] A. Bienfait, J. Pla, Y. Kubo, M. Stern, X. Zhou, C.C. Lo,C. Weis, T. Schenkel, M. Thewalt, D. Vion, D. Esteve, B. Julsgaard, K. Moelmer, J. Morton, and P. Bertet, Nature Nanotechnology 11, 253 (2015).
[4] S. Probst, A. Bienfait, P. Campagne-Ibarcq, J. J. Pla, B. Albanese, J. F. Da SilvaBarbosa, T. Schenkel, D. Vion, D. Esteve, K. Mlmer, J. J. L. Morton, R. Heeres, P.Bertet, Appl. Phys. Lett. 111, 202604 (2017)
[5] V. Ranjan et. al., in preparation (2019)
[6] V. Ranjan et. al., in preparation (2019)

* vishal.ranjan@cea.fr

# Near quantum limited broadband microwave amplification using non-linear superconducting circuits

Arpit Ranadive,* Luca Planat, and Nicolas Roch
*Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France*

Efficient low noise amplification is a crucial component for any system dealing with low amplitude signals. In parametric amplifiers gain is achieved by harmonically varying a system parameter [1]. Currently, Josephson parametric amplifiers(JPAs) can attain quantum limited amplification for microwave signals [2] [3] and constitute the workhorse of most of the experiments involving superconducting qubits. However, JPAs based on resonant structures constituted by one or several Josephson junctions are limited to low bandwidth and saturation power [4] [5]. These limitations can be overcome using Josephson meta-materials forming traveling wave parametric amplifiers(TWPAs). We present a new design of TWPA, made from an array of superconducting quantum interference devices(SQUIDs) covered by a thin dielectric and a top ground plane, forming a 50Ω non-linear transmission line [6] [7]. Our amplifier features a 3GHz bandwidth and -100 dBm input saturation power. Both these figures of merit constitute an order of magnitude improvement over traditional JPAs. The key to achieving optimal performances is the engineering of a gap in the dispersion relation of the transmission line to attain phase matching. This is obtained by periodically modulating the size of the SQUIDs, similarly to what is done with photonic crystals. Our simplified aluminum based two step fabrication technique and low footprint of these devices paves the way for on-chip integration of these broadband amplifiers with quantum devices.

[1] D. P. Howson et al., European electrical and electronic engineering series, London, McGraw-Hill (1970).
[2] C. M. Caves et al., Phys. Rev. D, vol. 26, pp. 1817–1839 (Oct 1982).
[3] R. Vijay et al., Review of Scientific Instruments, vol. 80, no. 11, p. 111101 (2009).
[4] M. Hatridge et al., Phys. Rev. B, vol. 83, p. 134501 (Apr 2011).
[5] J. Y. Mutus et al., Applied Physics Letters, vol. 103, no. 12, p. 122602 (2013).
[6] L. Planat et al., Preprint arXiv:1907.10158.
[7] L. Planat et al., Preprint arXiv:1907.10162.

* E-mail: arpit.ranadive@neel.cnrs.fr

# Absolute Single Ion Thermometry

Vincent Tugayé, Théo Henner, Samuel Guibal, Jean-Pierre Likforman, and Luca Guidoni*
*Laboratoire Matériaux et Phénomènes Quantiques,*
*UMR 7162 CNRS, Universitée Paris-Diderot,*
*Sorbonne Paris Cité, F-75205 Paris, France*

Laser cooled trapped ions offer the opportunity for a precise quantum control at the single particle level [1] that triggered the development of ion-based platforms dedicated to quantum information processing [2].

Since the first demonstrations of laser cooling of trapped ions, experimental thermometry tools have been developed together with theoretical models predicting stationary temperatures, for instance in the case of Doppler cooling [3].

Here, we present a new, fast and simple thermometry technique able to measure the absolute local temperature of a single trapped ion. The technique is based on the velocity-dependent spectral shape of a quasi-dark resonance tailored in a $J \rightarrow J$ transition. The dark resonance is obtained by addressing the transition with both an intense circularly polarised "pump" beam and a weak $\pi$ polarised "probe" beam. Absolute sensitivity is obtained by fitting the experimental data to the solutions of the optical Bloch equations, in the absence of adjustable "ad hoc" parameters accounting for the phase drifts of laser beams. This becomes possible because we chose a geometry in which the dark resonance is formed using two laser beams issued from the same laser source. We tested the method in an experiment on a single $^{88}$Sr+ ion cooled in a surface radio-frequency trap. We first used our technique to measure the heating-rate of the surface trap. In a second experiment we measured the temperature of the ion as a function of cooling laser detuning in the Doppler regime [4]. In the range of 0.5 to 3mK, accessed in this experiment, the results agree with theoretical calculations performed without any adjustable parameters [3]. We also demonstrateed sub-Doppler cooling of the ion, reaching a temperature of 0.20(5) mK taking advantage of a mechanism reminiscent of EIT cooling but in a completely different regime with respect to previous realisations. A numerical analysis allowed us to evaluate, that, using this technique, the accessible temperatures are in a range of 20$\mu$K to 200mK. This simple and reliable method opens the way to fast measurements of single-ion temperatures in experiments such as heat transport in ion chains.

[1] D. J. Wineland, Rev. Mod. Phys. **85**, 1103 (2013).
[2] R. Blatt and D. Wineland, Nature **453**, 1008 (2008). C. Monroe, R. Raussendorf, A. Ruthven, K. R. Brown, P. Maunz, L.-M. Duan, and J. Kim, Phys. Rev. A **89**, 022317 (2014).
[3] D. J. Wineland, W. M. Itano, J. C. Bergquist, and R. G. Hulet, Phys. Rev. A **36**, 2220 (1987).
[4] S. Knunz, M. Herrmann, V. Batteiger, G. Saatho, T. W. Hansch, and T. Udem, Phys. Rev. A **85**, 023427 (2012).

* jean-pierre.likforman@univ-paris-diderot.fr

# Spin-mechanics with particles in Paul traps

T. Delord, P. Huillery, L. Nicolas and G. Hétet[1*]
[1] *Laboratoire de Physique de l'Ecole normale supérieure, ENS, Université PSL, CNRS, Sorbonne Université, Université Paris-Diderot, Sorbonne Paris Cité, Paris, France.*

Observing and controlling macroscopic quantum systems has long been a driving force in research on quantum physics. In this endeavor, coupling individual quantum systems to mechanical oscillators is of great interest. While both read-out of mechanical motion using two-level spin systems and spin read-out using oscillators have been demonstrated, temperature control of the motion of a macroscopic object using electronic spins is still a daunting task.

We will present our observations of spin-dependent torque and dynamical back-action from a micro-diamond levitating in a Paul Trap [2]. Using a combination of microwave and laser excitation enables the spin of nitrogen-vacancy centers to act on the diamond orientation and to observe cooling of the diamond libration. Further, driving the system in the non-linear regime, we demonstrate bistability and self-sustained lasing of the librational mode.

The final temperature is currently limited by microwave excitation on the blue side of the spin-resonance since the trapping frequency is lower than the spin decoherence rate. We discuss ways to achieve spin-cooling to the ground state and present first steps towards a platform that uses levitating magnets and CVD grown diamond samples in order to reach the sideband resolved regime [3].

[1] Delord T. et al. Phys. Rev. Lett. 121 053602 (2018).
[2] Delord T., et al. arXiv :1905.11509 (2019)
[3] Huillery P. et al. ArXiv 1903.09699 (2019).

* gabriel.hetet@lpa.ens.fr

# Spectrum analyzer based on NV centers in diamond

Simone Magaletti[1], Ludovic Mayer[1], Loïc Toraille[2], Jean-François Roch[2], and Thierry Debuisschert[1*]
[1]*Thales Research and Technology,*
*1 av. Fresnel, 91767 Palaiseau, France*
[2]*Laboratoire Aimé Cotton, CNRS,*
*ENS Paris-Saclay, Batiment 505,*
*Rue du Belvédère, 91400 Orsay, France*

The Nitrogen Vacancy (NV) centers are considered, for their optical and spin proprieties, promising candidates for quantum sensing applications. In this work, the spin-dependent optical proprieties of a NV centers ensemble are exploited in order to realize a spectrum analyzer.

To do that, a static magnetic field gradient, generated by a permanent magnet, induces a spatial dependent Zeeman shift to the NV centers present in the diamond : the NV center resonance frequency is so correlated to a defined position in the diamond [1]. A wide field imaging system collects the fluorescence of the NV centers while they are continuously pumped by a green (532nm) laser. A microwave magnetic field, resonant with the NV center transition, will cause a drop of photoluminescence, visible on the image, at a well-defined position. Knowing the static magnetic field at that position, the microwave frequencies can be deduced.

The device is able to achieve a dynamic range of 30 dB, a frequency range of 25 GHz and a limit resolution (frequency dependent) of 1 MHz.

The Nitrogen nuclear spin polarization by pure optical means near both ground state and excited state level anti-crossing has been also investigated [2]. A quite large range of polarization efficiency has been observed, allowing a better frequency resolution. The microwave power is also one of the causes inducing a linewidth spectral broadening. This phenomenon is characteristic of any two levels systems. The possibility of measuring the amplitude of the microwave magnetic field looking at the linewidth of the resonance is hence studied and some preliminary results are presented. The future perspective could be near-field microwave antenna characterization.

[1] M. Chipaux et al., Applied Physics Letters, 107, 233502 (2015).
[2] R.Fisher et al., Physical Review B, 87, 125207 (2013)

* thierry.debuisschert@thalesgroup.com

## Imaging and manipulating cold atoms through a multimode fiber

Nicolas Vitrant[1], Sebastien Garcia[1], Kilian Müller[1], Merlin Enault-Dautheribes[1], and Alexei Ourjoumtsev[1]*
[1] *Jeunes Équipes de l'Institut de Physique du Collège de France,*
*11 place Marcelin Berthelot, 75005 Paris, France*

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

The work we will present aims at transferring this technique to the field of cold atoms : using a multimode fiber, we are able to transport a small cloud of cold $^{87}$Rb atoms with an optical conveyor belt [4] at about $150\,\mu\mathrm{m}$ from the fiber tip. We can then load them in a small optical tweezer with a waist of $1.2\,\mu\mathrm{m}$, produced through the fiber by optical phase conjugation. By characterizing the propagation of light modes inside the fiber, from the random speckle field outputting the multimode fiber (see figure 1), we reconstruct absorption images of the trapped atoms (see Figure 2).

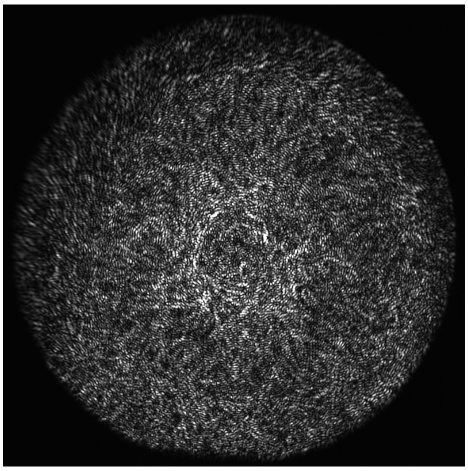


**Figure 1.** Image of light intensity outputting the mutlimode fiber, forming a random speckle.

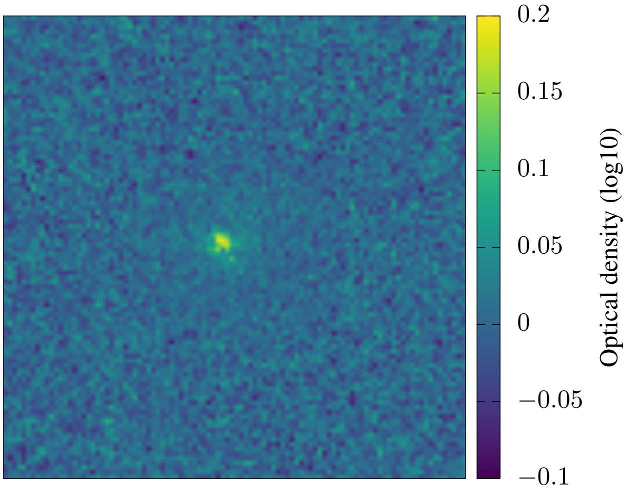



**Figure 2.** Absorption image through the multimode fiber of cold atoms captured in a micro-trap, reconstructed from the speckle. Dimension : $100 \times 100\,\mathrm{px} = 100 \times 100\,\mu\mathrm{m}$

[1] S. Popoff and al., Nat. Commun. 1 :81 (2010).
[2] Y. Choi and al., Phys. Rev. Lett. 109, 203901 (2012).
[3] I. N. Papadopoulos and al., Biomed. Opt. Express 4, 260-270 (2013).
[4] D. Schrader and al., Appl. Phys. B **73**, 819-824 (2001).

* sebastien.garcia@college-de-france.fr

# Prospects for vector Terahertz electrometry using the AC-Stark effect in two-photon spectroscopy of cold trapped HD$^+$ ions

Florin Lucian Constantin[1]*
[1] *Laboratoire PhLAM, CNRS UMR 8523, 59655 Villeneuve d'Ascq, France*

Atom-based detection of microwave fields provides SI-traceable measurements, sub-wavelength resolution, accuracy, precision and long-term reproducible operation, comparing to the traditional technology with an antenna and a solid-state detector. Laser spectroscopy of atomic Rydberg states was exploited for measuring microwave electric fields [1]. Light molecules provide dense spectra of rotational lines in the Terahertz domain. The hydrogen molecular ions are simple quantum systems for which ab-initio calculations provided accurately the energy levels [2] and the systematic frequency shifts [3]. This contribution proposes an approach to detect terahertz electric fields based on the measurement of the AC-Stark shift induced on rovibrational transitions of cold trapped HD$^+$ ions. Precisely, a THz electric field oscillating around 1.3 THz may be detected by the measurement of the AC-Stark shift induced on Zeeman components of the two-photon transition (v,L)=(0,0)→(2,0) of HD$^+$ at 55.9 THz. The two-photon line shape was calculated with a rate equation model and displays a resolution beyond the $10^{-12}$ level [4]. The AC-Stark shifts of the Zeeman components of the two-photon transition are calculated for each standard polarisation of a THz-wave coupled off-resonantly to HD$^+$ rotational energy levels. For example, the frequency shift of the transition between the stretched energy levels (Fig. 1) is higher than the 20-Hz two-photon linewidth for a frequency span of a few MHz around the relevant Zeeman components. The measurements of AC-Stark shifts for different hyperfine components and magnetic field orientations, as suggested in [5], may provide full characterisation of the THz-wave electric field vector. Sensitivity with 1 GHz bandwidth across the hyperfine structure of HD$^+$ energy levels may be obtained by a choice of the components of the rovibrational transition and by tuning using the Zeeman effect.

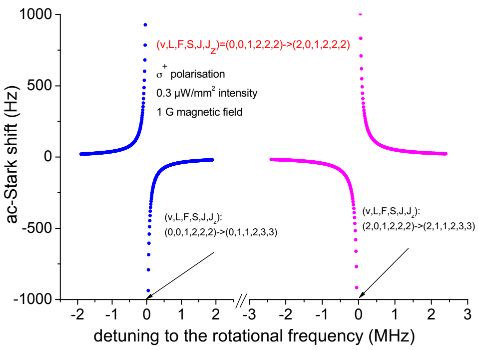



**Figure 1.** Dependence on the THz-wave detuning of the AC-Stark shift of the (v,L,F,S,J,J$_z$)=(0,0,1,2,2,2)→(2,0,1,2,2,2) component.

[1] J. Sedlacek *et al*, "Microwave electrometry with Rydberg atoms in a vapour cell using brignt atomic resonances," Nat. Phys. **8**, 819 (2012).
[2] V.I. Korobov, L. Hilico, J.-Ph. Karr, "Fundamental transitions and ionization energies of the hydrogen molecular ions with few ppt uncertainty," Phys. Rev. Lett. **118**, 233001 (2017).
[3] S. Schiller *et al*, "Static and dynamic polarizability and the Stark and blackbody-radiation frequency shifts of the molecular hydrogen ions $H_2^+$, HD$^+$, and $D_2^+$," Phys. Rev. A **89**, 052521 (2014).
[4] F.L. Constantin, "Double resonance two-photon spectroscopy of hydrogen molecular ions for improved determination of fundamental constants," IEEE TIM **69**, 2151 (2019).
[5] J. Koepsell *et al*, "Measuring the polarisation of electromagnetic fields using Rabi-rate measurements with spatial resolution : experiment and theory," Phys. Rev. A **95**, 053860 (2017).

# Quantum Simulation (QSIM)

# Scalable interfacing of quantum photonic platforms: solid-state single-photon sources and reconfigurable photonic circuits

**C. Antón[1], J. C. Loredo[1], G. Coppola[1], N. Viggianello[2], H. Ollivier[1], A. Harouri[1], N. Somaschi[3], A. Crespi[4,5], I. Sagnes[1], A. Lemaître[1], L. Lanco[1,6], R. Osellame[4,5], F. Sciarrino[2], P. Senellart[1]**

[1]*Center of Nanosciences and Nanotechnology - CNRS, Univ. Paris-Saclay, Route de Nozay, 91460, France*

[2]*Dipartimento di Fisica, Sapienza Universitá di Roma, Piazzale Aldo Moro 5, Roma I-00185, Italy*

[3]*Quandela, SAS, 86 Rue de Paris, 91400 Orsay, France*

[4]*Istituto di Fotonica e Nanotecnologie, CNR, P. Leonardo da Vinci, 32, Milano I-20133, Italy*

[5]*Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci, 32, Milano I-20133, Italy*

[6]*Université Paris Diderot - Paris 7, 75205 Paris CEDEX 13, France*

The development of optical quantum technologies relies on the use of many single-photons to solve milestone problems spanning from secure quantum communication, quantum simulation and distributed quantum computing. This requires efficient sources producing highly indistinguishable single-photons as well as photonic circuits showing high reconfigurability, phase stability and low losses.

Integrated photonics circuits on glass are an excellent platform to tackle a vast variety of complex quantum protocols such as Boson Sampling [1], quantum Fourier transforms [2], and quantum random walks [3,4]. So far, these photonic chips have been operated with heralded single-photon sources that show limited efficiency: these sources are typically operated with a brightness (i.e. probability to generate a photon-pair per pulse) around 1%, since the probability of generating more than one heralded photon scales as the source brightness.

Alternatively, electrically-controlled semiconductor quantum dots (QDs) coupled to microcavities have been shown recently to be near-optimal single-photon sources. They deliver true single- photon pulses with indistinguishability above 90% and brightness around 15% [5].

In this work we combine for the first time these two promising platforms, QD-based single- photon sources and an integrated photonic circuit, in order to demonstrate the potential of such interface for scaling up optical quantum protocols. The chosen case study in this experiment is quantum interference of three indistinguishable single-photons [6-8].

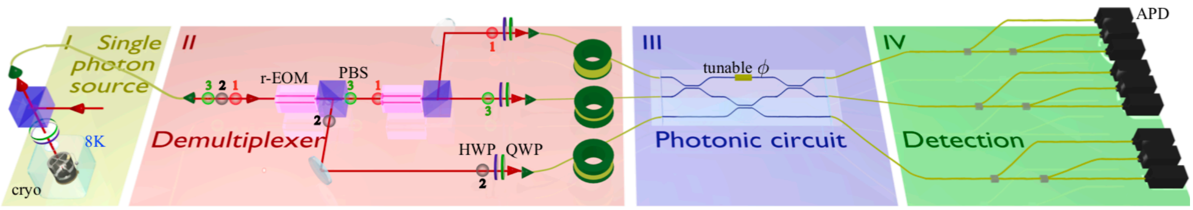



Fig. 1. **Experimental scheme of the three photon coalescence**. (I) Generation of single-photons from a QD-micropillar device under resonant fluorescence excitation. (II) Preparation of the three photons simultaneously arriving to the tritter input via active demultiplexing. (III) Photonic circuit of the tritter to perform the three photon coalescence. (IV) Detection of the quantum state of light at the tritter output.

The QD-cavity device is resonantly excited under pulsed excitation (at a high repetition rate of 324 MHz) to generate a stream of single-photons with $g^{(2)}(0)<5\%$ and indistinguishability >85% (between 80 ns delayed photons), see Fig. 1-I. We have developed a fast active demultiplexer to distribute three temporally distant single-photons into three spatial fiber modes, Fig. 1-II. The active photon-routing renders a three-single-photon generation rate of 3.9 kHz, three orders of magnitude higher than the same experiment performed with heralded single-photon sources [6].

The three photons are injected in the reconfigurable photonic tritter (see a sketch of the circuit in Fig. 1-III). The output quantum state of light is collected in three fibers, where pseudo-photon number resolving detection is implemented with nine standard Silicon avalanche photodiodes (see sketch in Fig. 1-IV). The combined detection of three photon coincidences in the detectors (at a rate of threefold coincidences of 0.25 Hz) allows the final reconstruction and characterization of the multi-photon coalescence state.

**References**

[1] N. Spagnolo, et al., Nature Photon. 8, 615 (2014).
[2] A Crespi, et al., Nature Commun. 7, 10469 (2016).
[3] L. Sansoni, et al., Phys. Rev. Lett. 108, 010502 (2012).
[4] A. Crespi, et al., Nature Photon. 7, 322 (2013).
[5] N. Somaschi, et al., Nature Photon. 10, 340 (2016).
[6] N. Spagnolo, et al., Nature Commun. 4, 1606 (2013).
[7] J. B. Spring, et al., Optica 4, 90 (2017).
[8] M. Zukowski, et al., Phys. Rev. A 55, 2564 (1997).

# Engineering two-photon wavefunction and exchange statistics in a semiconductor chip

S. Francesconi[1], F. Baboux[1], A. Raymond[1], N. Fabre[1], A. Lemaître[2], P. Milman[1], M. Amanti[1] and S. Ducci[1]

[1] *Laboratoire MPQ, USPC, Université de Paris - CNRS UMR 7162 Paris, France*

[2] *C2N, CNRS/Université Paris Sud, UMR 9001, 91460 Marcoussis, France*

Nonclassical states of light are key components for quantum information technologies: they combine the robustness to decoherence and the easy transmission of photons with the richness of quantum mechanics. Moreover, the possibility of encoding such states in high-dimensional degrees of freedom of photons (e.g. frequency, orbital angular momentum, …) offers a way to increase their non-classicality. Among these different degrees of freedom frequency is particular attractive thanks to its robustness to propagation in optical fibers and its capability to convey large scale of quantum information into a single spatial mode. Reaching a precise control over this degree of freedom is therefore desirable in order to employ the same source of quantum states of light in many different applications. In this framework, the technological maturity and optoelectronic capabilities of III-V materials make them an ideal platform to develop efficient and scalable devices to generate and manipulate frequency-encoded quantum states [1].

In this work, we exploit the high flexibility offered by Spontaneous Parametric Down Conversion in a semiconductor AlGaAs microcavity under a transverse pump geometry [2]. We demonstrate that tailoring the spatial profile (intensity and phase) of the pump beam enables the control of the spectral correlations and wavefunction symmetry of the photon pairs directly at the generation stage, without any post-selection. In particular, tuning the pump beam waist allows to produce correlated, anti-correlated and separable frequency states, while modifying the spatial phase allows to control the exchange statistics of the two photons state when they meet in a Hong-Ou-Mandel (HOM) interferometer. Fig. 1a) shows a sketch of the device for the latter case: using a spatial light modulator we can control the phase shift between the two halves of the pump beam which impinges of the waveguides with an angle θ. The first row of the right part of the figure reports the results for a flat phase (φ'=0) pump beam: the emitted two-photon state has an almost Gaussian join spectrum (Fig 1b) and in a HOM interferometer it shows a bunching behavior (Fig 1c- Fig 1d), typical of bosonic statistics. On the other hand, if we apply a pi phase shift (φ'=π), as shown in the second row, the joint spectrum presents a clear splitting in two lobes (Fig 1e) and the coincidence probability features a clear change to an anti-bunching behavior (Fig 1f-Fig 1e), typical of fermionic statistics [3].

These results, obtained with an integrated chip, at room temperature and telecom wavelength, could be harnessed to study the effect of exchange statistics in various quantum simulation problems, and to implement communication and computation protocols exploiting antisymmetric high-dimensional quantum states [3]. Moreover, undergoing studies have shown that more exotic nonclassical states, like Schrodinger's cat in frequency-time domain, can be generated with the same device, broadening the range of its possible applications in the quantum technology framework.

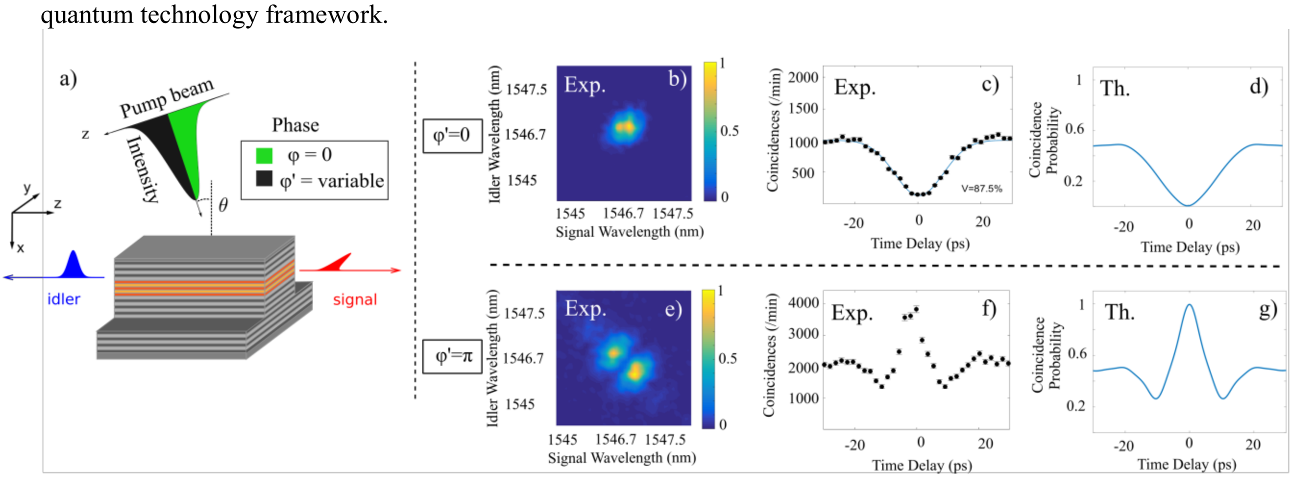



Figure 1: a) Sketch of the working principle of the device under transverse pump illumination; b-d) joint spectrum measured with a fiber spectrograph [4], corresponding experimental and numerical simulations data showing the two-photon interference in a HOM interferometer for a flat phase pump beam (φ'=0); e-g) joint spectrum and HOM interference for a pump beam with a pi phase shift (φ'=π).

[1] A. Orieux et al., Rep. Prog. Phys. 80, 076001 (2017).

[2] X. Caillet et al., Journal of Modern Optics 56, 232-239 (2009).

[3] S. Francesconi et al., in preparation.

[4] A. Eckstein et al., Laser and Photonics Reviews 8, L76-L80 (2014).

# A laser-cooled Bose-Einstein Condensate

Alban Urvoy[1,2*] and Zachary Vendeiro[1], Joshua Ramette[1], Albert Adiyatullin[1], and Vladan Vuletić[1]
[1]*Department of Physics, MIT-Harvard Center for Ultracold Atoms and Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA*
[2]*Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, 4 place Jussieu, 75252 Paris, France*

Laser cooling methods are virtually ubiquitous for the production of ultracold quantum gases. Yet in order to reach quantum degeneracy, a complementary step of lossy and inefficient evaporative cooling has so far been required (with few specific exceptions [1, 2]).

Here, we present the first realization of direct laser cooling of rubidium atoms to Bose-Einstein condensation [3]. The method relies on Raman cooling in an optical dipole trap. A careful tuning of trapping and cooling parameters is required to evade inelastic loss and heating mechanism, but the method should still be generic enough to be applicable to various other species. We will discuss the general requirements for efficient cooling and crossing quantum degeneracy, as well as prospects opened up by our results for the realization of a collisionless atom laser.

[1] S. Stellmer, B. Pasquiou, R. Grimm and F. Schreck "Laser Cooling to Quantum Degeneracy", Phys. Rev. Lett. **110**, 263003 (2013).
[2] J. Hu*, A. Urvoy*, Z. Vendeiro, V. Crépel, W. Chen and V. Vuletić, "Creation of a Bose-condensed gas of $^{87}$Rb by laser cooling", Science **358**, 1078–1080 (2017).
[3] A. Urvoy*, Z. Vendeiro*, J. Ramette, A. Adiyatullin and V. Vuletić, "Direct Laser Cooling to Bose-Einstein Condensation in a Dipole Trap", Phys. Rev. Lett. **122**, 203202 (2019).

* alban.urvoy@lkb.upmc.fr

# Observation of a topological phase in arrays of Rydberg atoms

Vincent Lienhard[1], Sylvain de Léséleuc[1], Pascal Scholl[1], Daniel Barredo[1], Sebastian Weber[2], Nicolai Lang[2], Hans Peter Büchler[2], Thierry Lahaye[1] and Antoine Browaeys[1]*
[1]*Laboratoire Charles Fabry, Institut d'Optique Graduate School, CNRS, Université Paris-Saclay, F-91127 Palaiseau Cedex, France*
[2]*Institute for Theoretical Physics III and Center for Integrated Quantum Science and Technology, University of Stuttgart, 70550 Stuttgart, Germany*

For a few decades, topological phases have emerged as a new framework to classify phases of matter. They are explored both theoretically and experimentally and are seen as one of the hottest topics in condensed matter physics. Consequently, several experimental quantum simulation platforms have tried to implement Hamiltonians exhibiting such topological properties, and observed their expected features, mainly in the single-particle regime.

In this poster, I will explain how we were able to engineer the Su-Schrieffer-Heeger (SSH) model, on our platform based on single Rubidium atoms trapped in versatile arrays of optical tweezers and excited to Rydberg states [1]. The SSH model is one of the simplest model expected to host topological states of matter [2]. I will show how we went beyond the single-particle regime and observed a many-body symmetry protecting topological phase [3].

I will also present how we can implement some complex hopping amplitude using the intrinsic spin-orbit coupling of the dipole-dipole interaction between Rydberg atoms, leading to the engineering of artificial gauge fields. I will probe the effect of this artificial magnetic field by the experimental observation of the chiral motion of a hopping particle, on a minimal system of three Rydberg atoms. On larger systems, we expect to observe chiral edge states, signatures of topology in two-dimensional structures.

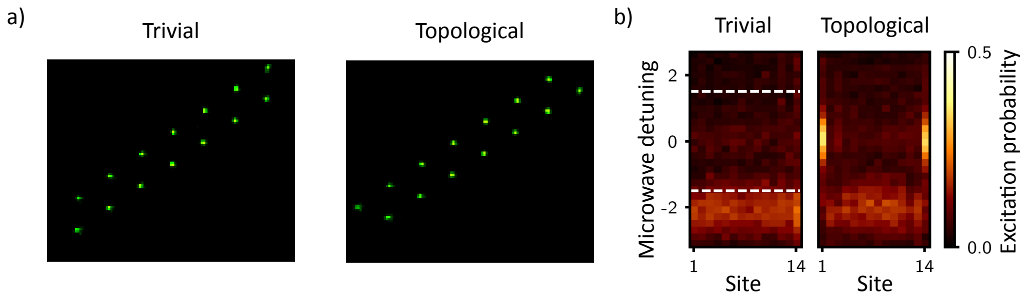



FIG. 1. Probing the single-particle signature of topology in the SSH model. (a) : Single-shot fluorescence images of the atomic arrays used to simulate the two configurations of the SSH model, the trivial and the topological ones. (b) : Site-dependent single-particle spectroscopy of the SSH chain in its two configurations. The spectroscopy in the topological case reveals the presence of edge states, signatures of topology.

[1] S. de Léséleuc, V. Lienhard, P. Scholl, D. Barredo, S. Weber, N. Lang, H. P. Büchler, T. Lahaye and A. Browaeys, "Observation of a symmetry-protected topological phase of interacting bosons with Rydberg atoms", Science **365**, 775-780 (2019).
[2] J. Asbóth, L. Oroszlány, and A. Pályi, "A Short Course on Topological Insulators", arXiv :1509.02295 (2016).
[3] X.Chen, Z.-C. Gu, Z.-X. Liu and X.-G. Wen, "Symmetry protected topological orders in interacting bosonic systems", Science **338**, 1604-1606 (2012).
Xie Chen, Zheng-Cheng Gu, Zheng-Xin Liu, Xiao-Gang Wen

* vincent.lienhard@institutoptique.fr

# Towards deterministic photon-photon interaction mediated by Rydberg excitation in an optical cavity

Merlin Enault-Dautheribes [1], Julien Vaneecloo [1], Sébastien Garcia[1], Nicolas Vitrant and Alexei Ourjoumtsev [1]
[1]*Quantum Photonics team, Institut de Physique - Collège de France,*
*11 place Marcelin Berthelot, 75231 Paris, France*

Reaching the regime of strong interaction between individual photons is a long standing goal of quantum optics. Its realization would open new perspectives, in particular for the fields of quantum information processing and quantum simulation. We present an experimental platform aiming at the creation of deterministic photon-photon interactions. Optical photons can be converted into Rydberg excitations by using electromagnetically induced transparency (EIT,) to take advantage of the strong interaction present between Rydberg atoms [1]. In this context, strongl non-linear regimes have been reached in cold atomic ensemble with single photon excitations [2]. In order to further increase the non-linearity, the atomic cloud can be placed into a cavity. A single Rydberg excitation generated by a first photon could thus change the optical response of the atomic gas surrounded by the cavity, such that the phase of a second incoming photon shifts or even flips. Such strong deterministic photon-photon interactions could lead to the creation of controlled phase-gate [3], non-classical states of light [4] and could allow simulations of two-dimensional condensed matter physics systems such as a charged particle gas in a magnetic field [5].

In the construction of our experimental platform, one of the initial steps is to stabilize the lasers frequencies due to the width of the targeted Rydberg lines. The stabilisation is achieved via an ultra-stable cavity being the central part of a chained frequency control of our lasers. To obtain a cold atomic gas, we use a 2D magneto-optical trap (MOT) of Rubidium which supplies a 3D MOT located in the main vacuum chamber, where an atomic gas is compressed and cooled down. Using a dipolar conveyor belt, the atomic ensemble is transported over 32.5 millimetres to a non-planar cavity, as shown in figure 2. After optical pumping of the cloud, a probe beam and intense blue light excite conjointly the atoms. Currently, by using a two-photon excitation scheme, EIT is witnessed. We present the latest measurements and calibration of our setup.

In the future, tailoring the set of parameters such as the ensemble size ans density, the laser powers and detunings, and the cavity length will allow the study of aforementioned phenomena.

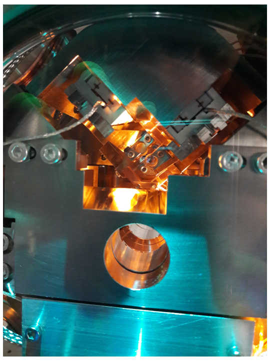


FIGURE 1: Picture of the non-planar cavity.

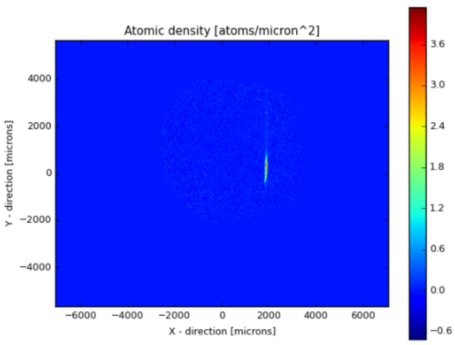



FIGURE 2: Absorption imaging of the atomic cloud after transport.

[1] Gaëtan & al, "Observation of collective excitation of two individual atoms in the Rydberg blockade regime", Nat. Phy. vol. 5, p. 115–118 (2009)

[2] Peyronel & al, "Quantum nonlinear optics with single photons enabled by strongly interacting atoms", Nat. vol. 488, p. 57–60 (2012)

[3] Das & al, "Photonic Controlled-Phase Gates Through Rydberg Blockade in Optical Cavities", Phys. Rev. A 93, 040303 (2016)

[4] Li & al, "Entanglement between light and an optical atomic excitation", Nat. vol. 498, p. 466–469 (2013)

[5] Schine & al, "Synthetic Landau levels for photons", Nat. vol. 534, p. 671–675 (2016)

# Quantum Processing, Algorithm, & Computing (QPAC)

# Graphical verification of large scale quantum processes

Titouan Carette*
*MOCQUA, LORIA, Université de Lorraine, INRIA, CNRS, Nancy, France*

The linear algebraic description of quantum mechanic involves a large number of degrees of freedom that scale exponentialy. As a consequence, the simulation or verification of large scale quantum processes is in general intractable on a classical computer. However, dealing with a fixed set of gates, one can still provide efficient descriptions of restricted classes of processes. Some finite sets of gates are even aproximatively universal: they can approximate with arbitrary precision any unitary matrix. The circuit model is a graphical way to represent unitaries as compositon of elementary gates. It has been widely used to describe quantum protocols and algorithms.

The main drawback of circuits is that no complete equational theory is known for an arbitrary number of qubits. The only way, in general, to check if two circuits are equivalent is to compute the associated matrices. ZX-calculus [1] is a graphical language based on non-unitary gates. ZX diagramms can be thought of as lax circuits. This language was shown universal and complete [2] with a small number of equations and for any number of qubits. ZX-calculus has recently been succesfully applied to circuits optimization, providing the state of the art T-count reducing strategy [3].

We present two recent extensions of the ZX-calculus. First, a universal and complete equational theory for mixed state quantum mechanic [4]. It allows to represent in the same framework classical and quantum aspects of quantum protocols. The second extension allows for a uniform treatment of processes for an arbitrary number of qubits [5]. As an example we will use those extensions to provide a compact graphical representation and verification of Simon's algorithm [6].

[1] B. Coecke and R. Duncan, "Interacting quantum observables: categorical algebra and diagrammatics", New Journal of Physics, 2011.
[2] E. Jeandel, S. Perdrix and R. Vilmart, "A complete axiomatisation of the ZX-calculus for Clifford+ T quantum mechanics", LICS '18 Proceedings of the 33rd Annual ACM/IEEE Symposium on Logic in Computer Science, Pages 559-568.
[3] A. Kissinger and J. van de Wetering, "Reducing T-count with the ZX-calculus", arXiv preprint arXiv:1903.10477, 2019.
[4] T. Carette, E. Jeandel, S. Perdrix and R. Vilmart, "Completeness of Graphical Languages for Mixed States Quantum Mechanics", ICALP 2019.
[5] T. Carette, D. Horsman and S. Perdrix, "SZX-calculus: Scalable Graphical Quantum Reasoning", MFCS 2019.
[6] D.R. Simon, "On the power of quantum computation", Foundations of Computer Science, 1994 Proceedings., 35th Annual Symposium on: 116–123.

* titouan.carette@loria.fr

# Fault-Tolerant Quantum Speedup With Constant Depth Circuits

Rawad Mezher[1 2] and Damian Markham [1],
[1]*Laboratoire d'Informatique de Paris 6,*
*CNRS, Sorbonne Université, 4 place Jussieu,*
*75252 Paris Cedex 05, France*
[2] *Laboratoire de Physique Appliquée, Faculty of Sciences 2,*
*Lebanese University, 90656 Fanar, Lebanon*

**Introduction**

Achieving a quantum-over-classical advantage is an important milestone in the field of quantum computing. Although, to date, there are examples of quantum algorithms which outperform classical algorithms, on the practical level, these algorithms in general require quantum computers with a suitable level of fault-tolerance and scalability [1], the likes of which appear to be out of the reach of current technological developments [2]. An interesting question is thus, what can be done with so-called $sub\text{-}universal$ quantum devices which are not universal in the sense that they can perform any quantum operation, are realizable in principle by our current technologies, but nevertheless capture the power of quantum computing. Examples of such devices are those of [1, 3–7]. Sampling from the output probability distribution of these devices (even up to constant error in the $l_1$ norm) has been shown to be classically impossible efficiently, provided widely believed complexity theoretic conjectures hold [1, 7]. In this sense these devices are said to demonstrate a $quantum\ speedup$. For proofs of quantum speedup, the standard conjectures are of the form [1, 4–6, 8–10] **I)** The polynomial hierarchy does not collapse to the third level [11]. **II)** Average case approximation of the output probabilities (up to constant relative error) of the associated problem (usually worst-case ♯P-hard) is also hard (♯P). **III)** The quantum circuit families considered output distributions which are not too peaked - technically known as anti-concentration [5, 6, 10].

**Quantum speedup robust against noise.**

A main obstacle in the way of achieving a quantum speedup is noise, which destroys whatever quantum advantage a quantum device possesses [10, 12, 13]. To counter this problem, in this work, we provide an example of 2D graph state architectures with practically desired properties such as nearest neighbor interactions, and regular structure which, when measured at fixed angles non-adaptively, gives rise to output probabilities whose sampling shows a quantum speedup. Crucially, this quantum speedup is $robust$ to general noise models, because the qubits of these graph states are based on a particular quantum error correcting code [14].

Furthermore, in our case we only require two complexity theoretic conjectures ( **I)** and **II)** ). This is because our construction is based on ensembles of random unitaries called approximate unitary 2-designs [15], in which the anti-concentration conjecture ( **III)** ) can be proven explicitly [5, 6]. To date, the minimal number of complexity theoretic conjectures needed in proofs of quantum speedup is two, therefore our construction demonstrates a quantum speedup conditioned on a minimal number of complexity theoretic conjectures.

The overhead of physical qubits per single logical qubit required to achieve fault-tolerant, robust quantum speedup in our case is only poly-logarithmically worse than that in the robust quantum speedup proposal of [10], which only corrects for bit-flip errors.

As a final remark, our sampling problem can be viewed in the circuit model picture as a $constant$ $depth$ circuit acting on a polynomial number of ancilla qubits. Therefore, we present an example of a quantum circuit with constant depth giving rise to a sampling problem which demonstrates a quantum speedup, and which is robust to noise.

[1] M.J Bremner,R. Jozsa, and D.J Shepherd , In Proceedings of the Royal Society of London A : Mathematical, Physical and Engineering Sciences p. rspa20100301 (2010).
[2] J. Preskill, Quantum, 2, 79 (2018).
[3] A. W. Harrow and S. Mehraban, arXiv : 1809.06957 (2018)
[4] J. Bermejo-Vega, D. Hangleiter, , M. Schwarz, R. Raussendorf, and J. Eisert, arXiv :1703.00466 (2017).
[5] D. Hangleiter, J. Bermejo-Vega, M. Schwarz, and J. Eisert, arXiv :1706.03786 (2017).
[6] R. L. Mann, and M. J. Bremner, arXiv :1711.00686 (2017).

[7] S. Aaronson and A. Arkhipov, in Proceedings of the forty- third annual ACM symposium on Theory of computing (ACM), pp. 333-342. (2011).

[8] X. Gao, S. T.Wang, and L. M. Duan,Phys.Rev.Lett, 118 (4), 040502 (2017).

[9] M.J Bremner, A. Montanaro, and D.J Shepherd Phys. Rev. Lett. , 117(8), 080501 (2016)

[10] M.J Bremner,A. Montanaro, A., and D.J Shepherd, arXiv preprint arXiv :1610.01808 (2016).

[11] B. M. Terhal and D. P. DiVincenzo, Quantum Information and Computation 4, 134-145 (2004).

[12] K. Bu, and D.E Koh, arXiv preprint arXiv :1902.11257 (2019).

[13] X. Gao, and L. Duan, arXiv preprint arXiv :1810.03176 (2018).

[14] H. Bombin and M.A. Martin-Delgado,arXiv :quant-ph/0605138v3 (2007).

[15] R. Mezher, J. Ghalbouni, J. Dgheim, and D. Markham, Phys. Rev. A 97(2), 022333 (2018).

[16] A. Broadbent, A., J. Fitzsimons,and E. Kashefi In 50th Annual IEEE Symposium on Foundations of Computer Science (pp. 517-526). IEEE (2009).

[17] S. Bravyi and A. Kitaev, Phys. Rev. A 71(2), 022316 (2005).

[18] J. Haah, M.B Hastings, D. Poulin, and D. Wecker, arXiv preprint arXiv :1703.07847 (2017).

[19] A.J Landahl,J.T Anderson, and P.R Rice. arXiv preprint arXiv :1108.5738 (2011).

[20] F. Watson, . Performance of topological codes for quantum error correction (2015).

[21] E. Dennis, A. Kitaev, A.J Landahl, and J. Preskill. Journal of Mathematical Physics, 43(9), 4452-4505 (2002).

# Mode selective photon addition

Ganaël Roeland[1], Valentina Parigi[1], Nicolas Treps[1]
[1]*Laboratoire Kastler Brossel, Sorbonne Université, ENS-PSL Research University, Collège de France, Centre National de la Recherche Scientifique, 4 place Jussieu, F-75252 Paris, France*

In the context of quantum information, developing quantum technologies that give access to quantum advantage over classical computation is one of the main goal of recent research. Light is a promising physical system to encode and process information, owing to its good resilience to decoherence. In the continuous variables approach, where the field is described by phase and amplitude quadratures, it is possible to entangle deterministically high-dimensional multimode states [1]. To achieve quantum advantage from these states, one can rely on nonlinear operations to produce non-Gaussian states. This has been achieved by mode selective photon subtraction [2]. Here we theoretically show that mode selective photon addition is also achievable, and we highlight the differences between the two operations.

Photon addition refers to the process that aims at adding a single photon to an optical beam, called the signal. This can be achieved through parametric down conversion in a nonlinear medium. The signal beam goes through the crystal which is pumped by a classical field. A photon from the pump splits into two half-energy photons, one of which adds up to the signal. The remaining photon is used to herald the probabilistic process : provided the remaining photon is detected, a photon is added to the signal at the output.

To compare addition with subtraction, one can look at the output purity of the signal, since both processes may add or subtract to/from more than one mode. Intuitively it is impossible to subtract a photon form vacuum. This gives an advantage to subtraction over addition.

However in terms of Wigner function negativity of the output signal state, photon addition shows an advantage over subtraction : any added state has its Wigner function negative, while it is not the case for subtracted states [3]. In order to keep both advantages, one needs to ensure mode selectivity. To achieve it with the above described nonlinear process, one needs to satisfy some conditions : group velocity matching between the pump beam and the signal beam, and long enough crystal condition. Under these conditions, we show that the process adds a photon in only one spectral mode and that this spectral mode is given by the pump spectral mode. Going beyond the assumptions made to show the results, simulations in a KDP crystal show that mode selectivity holds in realistic conditions.

[1] S. Yokoyama, R. Ukai, S. C. Armstrong, C. Sornphiphatphong, T. Kaji, S. Suzuki, J.-i. Yoshikawa, H. Yonezawa, N. C. Menicucci, and A. Furusawa. “Ultra-Large-Scale Continuous-Variable Cluster States Multiplexed in the Time Domain.” Nature Photon **7**, 982 (2013).

[2] Y.-S. Ra, A. Dufour, M. Walschaers, C. Jacquard, T. Michel, C. Fabre, and N. Treps, ArXiv190110939 Quant-Ph (2019).

[3] M. Walschaers, C. Fabre, V. Parigi, and N. Treps, Phys. Rev. Lett. **119**, 183601 (2017).

# Cointegration of a CMOS Transimpedance Amplifier with a Quantum-Dot Device

L. Le Guevel[1*], G. Billiot[1], M.L.V. Tagliaferri[2], B. Cardoso Paz[1], M. Zurita[1], M. Cassé[1], M. Vinet[1], S. De Franceschi[2], X. Jehl[2], A.G.M. Jansen[2], and G. Pillonnet[1*]

[1] *Univ. Grenoble Alpes, CEA, LETI, Minatec Campus, F-38000 Grenoble, France*

[2] *Univ. Grenoble Alpes, CEA, IRIG, PHELIQS, F-38000 Grenoble, France*

Semiconductor quantum-dot structures could lead to a scalable quantum computer with thousands to billions of physical qubits on an $mm^2$-scale die. Current few qubit systems operate at cryogenic temperature connected to the control and read-out electronics placed at room temperature. Qubits scaling up introduces an exponentially growing number of interconnections leading to increasing demands for cryogenic refrigeration with the increased heat load for all the addressing wiring. CMOS electronics operating at low temperature gained interest in the past years to multiplex and generate the control signals with GHz bandwidth in view of a scalable qubit architecture[1].

Many technologies such as bulk CMOS or BiCMOS suffer from carrier freeze-out in the substrate at 4.2 K or below that deteriorates the analog performances. The industrial-ready Fully Depleted Silicon On Insulator (FDSOI) technology based on an extremely thin MOSFET channel-structure has promising properties at low temperatures such as lower dissipation and faster operation. The unique feature of the back-gate in FDSOI technology can also be used to significantly reduce the increase of threshold voltage at low temperature and thereby drastically reduce the power consumption as shown in [2]. Unlike custom CMOS designs matched to operate only at low temperatures, the FDSOI option offers both low-temperature operation and the benefits of a mature technology widespread among designers.

Using preliminary low-temperature characterizations of the FDSOI 28nm technology, we designed a low-power transimpedance amplifier (TIA) that is shown to operate down to 50 mK. Gain, bandwidth, and noise of the TIA were investigated from room to sub-1K temperature for different ranges of power consumption. The TIA has been cointegrated at low-temperature with a silicon quantum dot structure to assess the advantages and drawbacks of this cryogenic circuit for the electrical characterization of quantum dots and pave the way towards more optimized designs.

[1] E. Charbon et al., Cryo-CMOS for quantum computing, in *Electron Devices Meeting*, 2016

[2] H. Bohuslavskyi et al., Cryogenic Characterization of 28-nm FD-SOI Ring Oscillators with Energy Efficiency Optimization, in *IEEE Transactions on Electron Devices*, 2018

* loick.leguevel@cea.fr

# Single-Pass Generation of Spatially and Spectrally Multimode Squeezed States of Light

Tiphaine Kouadou[1], Luca La Volpe[1], Syamsundar De[1], Matthieu Ansquer[1],
Francesca Sansavini[1], Claude Fabre [1], Valentina Parigi[1] and Nicolas Treps[1]*
[1] *Laboratoire Kastler Brossel, CNRS, Sorbonne Université, 4 place Jussieu, 75005 Paris, France*

We propose the experimental and single-pass generation of spatially and spectrally multimode squeezed states of light at the rate of 156 MHz via noncollinear type-I Parametric Down Conversion (SPDC). These states constitute the building blocks of quantum complex networks named dual-rail cluster states [1]. Thanks to the robustness of their multipartite entanglement, cluster states are at the basis of Continuous-Variable Quantum Computation protocols such as Measurement Based Quantum Computation (MBQC) [2]. Moreover, the multimode structure of the squeezed states allows the simultaneous generation of multiple dual-rail clusters, thus increasing the available resource for computation.

Our source is a mode-locked Titanium-Sapphire laser, which delivers a train of 25-fs pulses at a rate of 156 MHz. In the frequency domain, this corresponds to a 45-nm-spectrum frequency comb centered at 795 nm. Part of the main laser source is used as a reference while the rest is frequency doubled in a 1-mm long BiBO crystal (Bismuth Borate), thus producing a frequency comb centered at 397 nm. Then, the up-converted pulses are injected into an optical cavity where they pump a type-I non-collinear SPDC process through a 2.8-mm long BBO crystal (Beta-Barium-Borate) placed at the beam waist. In this configuration, two-mode squeezed vacua (TMSV) are generated. Differently from the Optical Parametric Oscillators (OPOs), which are sources of multimode squeezed states [1],[3], signal and idler pulses do not resonate into a cavity and are emitted in free space at the rate of 156 MHz, thus preserving the multimode spatial structure of the light. After the nonlinear crystal, signal and idler pulses are entangled and constitute the building blocks of dual-rail cluster states. The pulses are subsequently superimposed on a balanced beam-splitter thus generating multimode squeezed states. In our experiment, the multimode features of the light are unveiled via mode-selective homodyne detection (LO-shaped homodyne detection), where the mode of the local oscillator (LO) is shaped both in the frequency domain - via pulse shaping techniques based on a Spatial Light Modulator (SLM) - and in the spatial domain (via spatial masks). This method allowed us to measure squeezing in four spectral modes (Hermite-Gaussian HG0 to HG3) (fig. 1) and to investigate, via the measurement of covariance matrices, the presence of correlations between modes displaying spatial and spectral features originating from the specific configuration of our experiment.

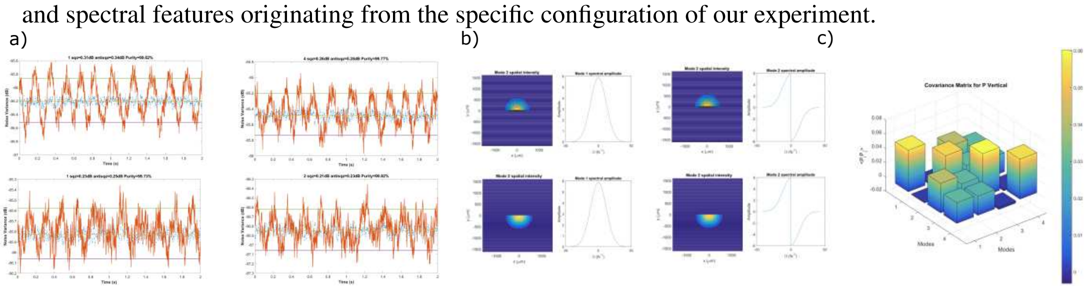



FIGURE 1: a) Multimode-squeezing-measurement curves. b) Experimental spatio-spectral modes. c) Covariance matrix associated to the spatio-spectral modes of fig. 1b).

[1] S. Yokoyama, R. Ukai, S. C. Armstrong, C. Sornphiphatphong, T. Kaji, S. Suzuki, J.-I. Yoshikawa, H. Yonezawa, N. C. Menicucci and A. Furusawa, "Ultra-large-scale continuous-variable cluster states multiplexed in the time domain", Nat. Phot. **7**, 982-986 (2013).

[2] R. Raussendorf, D. E. Browne and H. J. Briegel, "Measurement-based quantum computation on cluster states", Phys. Rev. A **68**, 022312 (2003).

[3] S. Gerke, J. Sperling, W. Vogel, Y. Cai, J. Roslund, N. Treps and C. Fabre, “Full Multipartite Entanglement of Frequency-Comb Gaussian States”, Phys. Rev. Lett., **114**, 050501 (2015).

* tiphaine.kouadou@lkb.upmc.fr

# Towards new technologies for miniaturized surface ion traps

T. Henner[1], J.-P. Likforman[1], L. Guidoni[1], Jing Tao[2], Yu Dian Lim[2], Peng Zhao[2], Chuan Seng Tan[2], , Anak Agung Alit Apriyana[2,3], Hong Yu Li[3*]
[1] *Matériaux et Phénomènes Quantiques, Université de Paris, CNRS, F-75013,Paris, France*
[2]*Nanyang Technological University, Singapore 639798*
[3]*Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR), Singapore 117685*

Laser cooled trapped ions are among the few physical systems in which quantum logic operations have been successfully demonstrated. First demonstrations have been obtained using macroscopically sized ion traps (tens of millimeters), but miniaturized devices can be successfully micro fabricated in a cleanroom (as it has been done, for example, at MPQ Paris-Diderot laboratory). Miniaturized surface ion traps allow for scalability, but a technology fully compatible with the conventional CMOS fabrication is still needed. We plan to develop hybrid ion traps (HIT), which will combine the use of a glass substrate (ideal for trapping) with a silicon interposer substrate (for laser beam steering and electronic connections). The envisioned embedding technology of the glass interposer into the Si substrate is such that HIT will be compatible with through-silicon-vias (TSV) and with mass production. HIT will allow us to implement photonic integrated circuits for ion addressing and readout [1] . Moreover, TSV technology opens the way to new trap designs (arrays and/or annular traps).

We recently demonstrated the functionality of a 80 $\mu$m sized surface trap built on a glass substrate compatible with the envisioned technology and the advanced cleanroom processes. For that preliminary demonstration we used a five wire geometry and loaded single ions and small ion strings of laser cooled $^{88}Sr^{+}$. Characterization of this trap using a novel technique for fast and reliable measurements of the heating rate of the traps [2] is in progress.

[1] K. K. Mehta, C. D. Bruzewicz, R. Mcconnell, R. J. Ram, J. M. Sage, and J. Chiaverini, “Integrated optical addressing of an ion qubit,” Nat. Nanotechnol. **11**, 1066–1070 (2016).

[2] V. Tugayé, J.-P. Likforman, S. Guibal, and L. Guidoni, "Absolute single-ion thermometry", Phys. Rev. A **99**, 023412 (2019).

* luca.guidoni@univ-paris-diderot.fr

# A graphical language for beam splitters

Alexandre Clément and Simon Perdrix*
*Université de Lorraine, CNRS, Inria, LORIA, F 54000 Nancy, France*

We introduce a graphical language based on a traced PROP to describe a family of systems in which a photon (or a beam) is sent in superposition of several positions and carries some additional quantum data represented by a qudit. Our systems are composed of polarizing beam splitters and black box unitary transformations on the data carried by the photon. This language can be used to represent protocols with indefinite causal order, including the so-called quantum switch.

Our language is equipped with a categorical denotational semantics and a simple complete axiomatization, the proof of completeness being based on a normal form. We also introduce a colored variant equipped with an analogous semantics and another complete axiomatization, which allows us to remove the useless wires, and has a simpler normal form and proof of completeness. Finally, we prove that extending our language with standard non-polarizing beam splitters allow us to perform any unitary transformation on the whole state of the photon.

* alexandre.clement@loria.fr, simon.perdrix@loria.fr

# Electron paramagnetic resonance spectroscopy of erbium doped insulators at millikelvin temperatures

Marianne Le Dantec [1], Milos Rancic [1], Emmanuel Flurin [1], Denis Vion [1], Daniel Estève [1], Patrice Bertet [1], Thierry Chanelière [2], Philippe Goldner [3], Sylvain Bertaina [4]

[1] Service de Physique de l'Etat Condensé, CEA Saclay, France
[2] Institut Néel, Grenoble, France
[3] Institut de Recherche de Chimie Paris, France
[4] Institut Matériaux Microélectronique Nanosciences de Provence, France

Rare-earth-ions are interesting physical systems because they have long lived states and record coherence times. This is due to their valence 4f electrons being very well shielded from the environment by the 5s and 5p filled shells. They are for example good candidates for quantum memories in the optical domain. Rare Earths with an odd number of electrons in the 4f shell are paramagnetic, with an electronic transition at microwave frequency that can be studied by standard EPR spectroscopy at GHz frequencies. For such transitions, coherence times around 50-100$\mu$s have been measured in the 1-2K temperature range [1]. Here we present our recent EPR results in 0.005% $Er : CaWO_4$. These measurements were recorded in a previously unstudied temperature regime for this material: sub-Kelvin temperature down to 10mK, using a superconducting micro-resonator and a superconducting parametric amplifier [2], [3]. We observe the longest recorded Hahn-echo decay for an electronic spin transition in an Erbium doped material, up to 1 ms. With two and three pulse echo measurements, we are further able to probe the ultra-slow spin dynamics at these low temperatures and compare our results with theoretical predictions of spin-spin and spin-lattice relaxation.

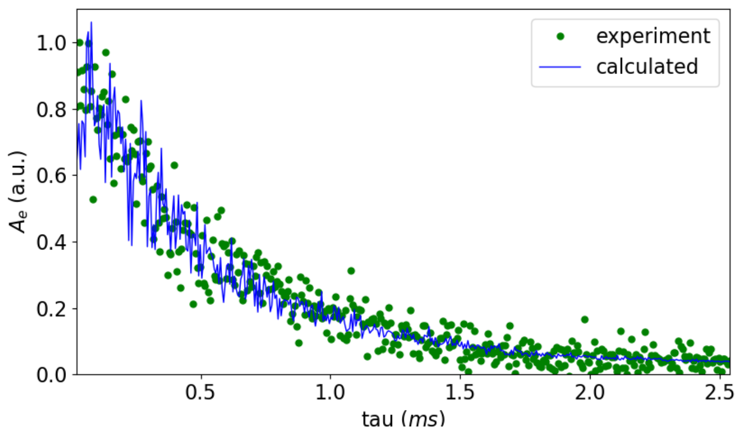



**Figure 1.** Hahn-echo decay at 10mK for an electron-spin transition of Erbium in $CaWO_4$

[1] S. Bertaina et al., Nature nanotechnology, vol. 2, no 1, p. 39, (2007).
[2] P. Haikka et al., Physical Review A, vol. 95, no 2, p. 022306, (2017).
[3] A. Bienfait et al., Nature nanotechnology, vol. 11, no 3, p. 253, (2016).

# Nanophotonic approaches for integrated quantum photonics

Stefano Pierini[1,2], Mackrine Nahra[1], Maxime Joos[2], Muhammad H. Muhammad[1,3], Viatcheslav Agafonov[4], Emmanuel Lhuillier[5], Fabien Geoffray[3], Valery Davydov[6], Quentin Glorieux[2], Elisabeth Giacobino[2], Sylvain Blaize[1], Alberto Bramati[2*] and Christophe Couteau[1]

[1]*University of Technology of Troyes and CNRS, Light, nanotechnologies & nanomaterials-L2n, 12 rue Marie Curie, 10300 Troyes, France,* [2]*Laboratoire Kastler Brossel, Sorbonne Université, Ecole Normale Supérieure and CNRS, 4 place Jussieu, 75252 Paris Cedex 05, France,* [3]*TeemPhotonics, 61 chemin du Vieux Chêne F-38240 Meylan, France,* [4]*University of Tours, Greman, UMR CNRS CEA 6157, F. Rabelais University, 37200 Tours, France,* [5]*Sorbonne Université, CNRS, Institut des NanoSciences de Paris, INSP, F-75005 Paris, France,* [6]*L. F. Vereshchagin Institute for High Pressure Physics, Russian Academy of Sciences, Troitsk, Moscow 108840, Russia*

Photons for quantum technologies have been identified early on as a very good candidate for carrying quantum information encoded onto them, either by polarization encoding, time encoding or spatial encoding. Quantum cryptography, quantum communications, quantum networks in general and quantum computing [1] are some of the applications targeted by what is now called quantum photonics. Nevertheless, it was pretty clear at an early stage that bulk optics for handling quantum states of light with photons would not be able to deliver what is needed for these technologies [2]. More recently, single photons, entangled photons and quantum optics in general have been coupled to more integrated approaches coming from classical optics in order to meet the requirements of scalability, reliability and efficiency for quantum technologies. In this presentation, we develop our recent advances in two different nanophotonic platforms for quantum photonics using elongated optical fibers and integrated glass waveguides made by the so-called ion-exchange technique. We also present our latest results on quantum nanoemitters that we plan to couple and incorporate with our photonics platforms. These nanoemitters are of two kinds: nanocrystals made of perovskites as well as silicon-vacancy defect centers in nanodiamonds. Some of their properties are developed in this work. We will then give the general steps necessary in order to couple these nanoemitters efficiently with our platforms in the near future.

[1] Acín, Antonio and Bloch, Immanuel and Buhrman, Harry and Calarco, Tommaso and Eichler, Christopher and Eisert, Jens and Esteve, Daniel and Gisin, Nicolas and Glaser, Steffen J and Jelezko, Fedor and others, "On the Quantum Foundations", New J. Phys. **8** (2018).

[2] AN Vamivakas and A Sergienko and A Fiore, "Special issue on integrated quantum photonics", Quant. Inf. J. **8** (2017).

* alberto.bramati@lkb.upmc.fr

# Quantum computing with arrays of neutral atoms

Adrien Signoles[1], Loïc Henriet[1]*
[1]*Pasqal, 2 avenue Augustin Fresnel, 91120 Palaiseau, France*

Our startup is aiming to develop a quantum computing platform made of controllable arrays of neutral atoms, based on the expertise acquired in the Browaeys' group at LCF. Pioneered works have indeed demonstrated that neutral atoms are extremely promising for providing largely scalable ensembles of well isolated qubits. We present here the machine we are currently building, where defect-free arrays of hundreds of qubits will be prepared by trapping atoms in optical tweezers, and entanglement will be generated by exciting them to Rydberg states. As a first realization we project to implement variational quantum computing algorithms, very promising in the framework of noisy intermediate scale quantum processors.

* loic@pasqal.io

## 5 Index of Authors

# Author Index

# 6 List of Participants

# List of participants

- Abbott Alastair
- Acin Antonio
- Aghababa Hossein
- Albanese Bartolo
- Albertinale Emanuele
- Alibart Olivier
- Ansel Quentin
- Ansquer Matthieu
- Appas Félicien
- Arnault François
- Auffèves Alexia
- Baboux Florent
- Baron Yoann
- Barral Raña David
- Belabas Nadia
- Bellomo Bruno
- Bertet Patrice
- Billard Marie
- Billaud Eric
- Bouscal Adrien
- Brunel Floriane
- Campagne-Ibarcq Philippe
- Carette Titouan
- Carmagnolle Léa
- Cavaillès Adrien

- Centrone Federico
- Chanelière Thierry
- Cimini Valeria
- Clément Alexandre
- Constantin Florin Lucian
- Coste Nathan
- Cotte Viviane
- Da Silva Barbosa Jéssica Fernanda
- Daldin Teodoro Marcio
- Dalidet Romain
- Darras Tom
- Davis Alex
- Defienne Hugo
- Degiovanni Pascal
- Delaye Philippe
- Delord Tom
- Diamanti Eleni
- Doutre Florent
- Dréau Anaïs
- Dubois François
- Ducci Sara
- Durand Alrik
- Dutier Gabriel
- Efetov Dmitri
- Enault-Dautheribes Merlin
- Etesse Jean
- Ezratty Olivier
- Fainsin David
- Fedrici Bruno
- Fellous Marco
- Filipovic Jovana
- Francesconi Saverio

- Fruleux Damien
- Garcia Sébastien
- Garcion Charles
- Geiger Remi
- Girit Çağlar
- Goldfarb Fabienne
- Goldner Philippe
- Gorceix Olivier
- Goswami Ashutosh
- Gouzien Élie
- Grangier Philippe
- Groeblacher Simon
- Grosshans Frédéric
- Guidoni Luca
- Guillaud Jérémie
- Henner Théo
- Henriet Loic
- Hercé Gaétan
- Hetet Gabriel
- Home Jonathan
- Hua Xin
- Jadot Baptiste
- Jaffali Hamza
- Jnane Hamza
- Kaiser Florian
- Keller Arne
- Kouadou Tiphaine
- Koukiou Flora
- Krebs Olivier
- Labonté Laurent
- Lafitte-Houssat Eloïse
- Lagarrigue Alek

- Lanco Loïc
- Lanzillotti Kimura Daniel
- Le Dantec Marianne
- Le Guevel Loïck
- Lecheminant Philippe
- Lee Dong-Ho
- Lee Moonjoo
- Lienhard Vincent
- Likforman Jean-Pierre
- Liu Shikang
- Magaletti Simone
- Magniez Frederic
- Maillette De Buy Wenniger Ilse
- Markham Damian
- Martin Vincent
- Martin Anthony
- Massé Gaël
- Mehdi Elham
- Meignant Clément
- Melalkia Mohamed
- Mezher Rawad
- Miatto Filippo
- Milazzo Nadia
- Millet Clément
- Montanaro Ashley
- Mouny Pierre-Antoine
- Murani Anil
- Nascimbene Sylvain
- Neves Simon
- Neveu Pascal
- Nieddu Thomas
- Northup Tracy

- Ollivier Hélène
- Oser Dorian
- Oudot Enky
- Ourjoumtsev Alexei
- Parekh Rhea
- Parigi Valentina
- Pastier Florian
- Pellet-Mary Clément
- Perrin Hélène
- Petit Thierry
- Petritis Dimitri
- Peugeot Ambroise
- Peyruchat Léo
- Picholle Eric
- Pierini Stefano
- Pigeon Simon
- Pingault Benjamin
- Pointard Benjamin
- Procopio Lorenzo M.
- Pruvost Laurence
- Rafayelyan Mushegh
- Ranadive Arpit
- Rancic Milos
- Ranjan Vishal
- Raptakis Adam
- Ray Tridib
- Raymond Arnault
- Renault Paul
- Restuccia Sara
- Ribordy Gregoire
- Rodriguez Anne
- Roeland Ganaël

- Roman Rodriguez Victor
- Rouchon Pierre
- Salas-Montiel Rafael
- Sangouard Nicolas
- Sansavini Francesca
- Sarlette Alain
- Sauder Greg
- Schiavon Matteo
- Senellart Pascale
- Serrano Garcia Diana
- Shettell Nathan
- Siegele Christian
- Signoles Adrien
- Somaschi Somaschi
- Tanzilli Sébastien
- Thomas Sarah
- Toffano Zeno
- Treps Nicolas
- Trigo Vidarte Luis
- Tualle-Brouri Rosa
- Turner Peter
- Urvoy Alban
- Vaneecloo Julien
- Verlot Pierre
- Vincent Benzoni
- Vion Denis
- Vitrant Nicolas
- Wade Peregrine
- Walschaers Mattia
- Wein Stephen
- Xu Xiaolun
- Yonamoto Yoshiki
- Zaquine Isabelle

http://gdriqfa.cnrs.fr/

**IQFA'X is organized at the CNRS Headquarters**

**by the board of the GDR and the members of the CNRS Institute of Physics (INP).**

**With the financial supports of**