GDR - IQFA, 5^{th} Colloquium
CNRS GDR 3322

GDR - Atomes Froids, 2^{nd} Colloquium
CNRS GDR 3577

Ecole Normale Supérieure de Lyon
November 17-19th, 2014

Book of Abstracts

ENS DE LYON

CENTRE BLAISE PASCAL

Program of the Colloquium

Monday, November 17, 2014

TIME	EVENT
9:30 am - 10:00 am	Opening of the conference - Opening of the conference
10:00 am - 10:30 am	New types of qubits - NQD (Amphithéatre Mérieux)
10:00 - 10:30	› Electrical manipulation of a single nuclear spin using a single molecular magnet based transistor - *Franck Balestro, Institut NEEL, CNRS, University of Grenoble Alpes*
10:30 am - 11:00 am	Coffee break (Atrium)
11:00 am - 12:00 pm	Quantum annealing and quantum simulation (Amphithéatre Mérieux) - Prof. Dr. Mathias Troyer (Inst. for Theoretische Physik, ETH Zürich)
12:00 pm - 1:30 pm	Lunch (Atrium)
1:30 pm - 2:00 pm	Quantum Information Storage - QIS (Amphithéatre Mérieux)
13:30 - 14:00	› Quantum memory for cylindrical vector beams - *Christophe Arnold, Laboratoire Kastler Brossel*
2:00 pm - 3:00 pm	Coherent manipulation of qubits - CMQ (Amphithéatre Mérieux)
14:00 - 14:30	› Correlations of microwave photons emitted by inelastic Cooper pair tunneling - *Alexander Grimm, Laboratoire de Transport Electronique Quantique et Supraconductivité*
14:30 - 15:00	› Long coherence times for Rydberg qubits on a superconducting atom chip - *Thanh Long NGUYEN, Laboratoire Kastler Brossel*
3:00 pm - 3:30 pm	Coffee break (Atrium)
3:30 pm - 4:30 pm	Electron and nuclear spin qubits using donors in silicon. (Amphithéatre Mérieux) - Prof. John Morton (University College London & London center for Nanotechnology)
4:30 pm - 6:00 pm	Poster session - Poster session in the Atrium
6:00 pm - 8:00 pm	Quantum simulation and information processing - QSP (Amphithéatre Mérieux)
18:10 - 19:10	› Les gaz ultra-froids : un monde quantique entre physique atomique et matière condensée - *Jean Dalibard, Laboratoire Kastler Brossel, Collège de France*
8:00 pm - 8:30 pm	Cocktail (Amphithéatre Mérieux)

Tuesday, November 18, 2014

TIME	EVENT
9:00 am - 10:00 am	Quantum walks with neutral atoms. (Amphithéatre Mérieux) - Prof. Dr. Dieter Meschede (Bonn University)
10:00 am - 11:00 am	Quantum simulation and information processing - QSP (Amphithéatre Mérieux)

10:00 - 10:30	› Hong-Ou-Mandel effect with matter waves - *Denis Boiron, (Institut d'Optique)*
10:30 - 11:00	› Suppression and Revival of Weak Localization through Manipulation of Time-Reversal Symmetry - *Valentin Volchkov, Laboratoire Charles Fabry*
11:00 am - 11:30 am	Coffee break (Atrium)
11:30 am - 12:30 pm	Quantum simulation and information processing - QSP (Amphithéatre Mérieux)
11:30 - 12:00	› Creation and tomography of entangled states in an atomic ensemble using an optical cavity - *Jérome Estève, Laboratoire Kastler Brossel*
12:00 - 12:30	› Generation of squeezing and entanglement in external degrees of freedom with a BEC in double wells - *Marie Bonneau, Atominstitut, Vienna University of Technology*
12:30 pm - 2:00 pm	Lunch (Atrium)
2:00 pm - 3:00 pm	Magnetism without magnetism: Physics with ultracold quantum gases (Amphithéatre Mérieux) - Prof. Dr. Klaus Sengstock (Hamburg University)
3:00 pm - 4:00 pm	Quantum simulation and information processing - QSP (Amphithéatre Mérieux)
15:00 - 15:30	› A Dipolar Quantum Gas to simulate Quantum Magnetism - *Laurent Vernac, Laboratoire de Physique des Lasers*
15:30 - 16:00	› Quantum simulation of dynamical lattice gauge models - *Enrique Rico Ortega, IPCMS (UMR 7504) and ISIS (UMR 7006)*
4:00 pm - 4:30 pm	Coffee break (Atrium)
4:30 pm - 5:30 pm	Using the Wigner function to calculate expectation values (Amphithéatre Mérieux) - Pr. Dr. Gerd Leuchs (University of Erlangen & Mac Planck Institute for the Science of Light)
5:30 pm - 7:00 pm	Poster session - Poster session in the Atrium
8:30 pm - 11:00 pm	Dinner

Wednesday, November 19, 2014

TIME	EVENT
9:00 am - 10:00 am	Causal relations in a quantum world. (Amphithéatre Mérieux) - Cyril Branciard (Institut Neel, Grenoble)
10:00 am - 10:30 am	Foundational aspects - FOUND (Amphithéatre Mérieux)
10:00 - 10:30	› 1D-atoms applied to Fundamental Quantum Mechanics - *Marcelo Santos, Universidade Federal de Minas Gerais*
10:30 am - 11:00 am	Coffee break (Atrium)
11:00 am - 12:30 pm	Quantum communication - QCOM (Amphithéatre Mérieux)
11:00 -	› Time-division demultiplexing for polarization-entangled photons - *Jonathan Lavoie, GAP*

11:30	*Quantique - University of Geneva*
11:30 - 12:00	› Self-testing quantum random number generator - *Anthony Martin, Group of Applied Physics, Université de Genève - Nicolas Brunner, Institute for Theoretical Physics, Geneve*
12:00 - 12:30	› Electrically Tunable Bright Sources of Indistinguishable Single Photons - *Niccolo Somaschi, Laboratoire des Photonique et de Nanostructure-CNRS*
12:30 pm - 2:00 pm	Lunch (Atrium)
2:00 pm - 3:00 pm	Electron quantum optics (Amphithéatre Mérieux) - Gwendal Fève (Laboratoire Pierre Aigrain, ENS Paris)
3:00 pm - 3:30 pm	New types of qubits - NQD (Amphithéatre Mérieux)
15:00 - 15:30	› Experimental boson sampling with integrated photonics - *Fabio Sciarrino, Dipartimento di Fisica [Rome]*
3:30 pm - 4:00 pm	Coherent manipulation of qubits - CMQ (Amphithéatre Mérieux)
15:30 - 16:00	› Multiplexed control and single-shot readout of transmon qubits - *Vivien Schmitt, Quantronics Group*

Contents

1 Welcome to the conference on "Advances in quantum information and quantum simulation"

1.1 Aim of the workshop

This conference is organized by the CNRS[1] research networks on "*Quantum Information, Foundations and Applications*" (**GDR - IQFA**) and "*Cold Atoms*" (**GDR - Cold Atoms**). It will focus on the recent developments in quantum technologies for quantum information, quantum simulations and quantum metrology. A particular enmphasis will be put on recent progresses in quantum simulation based on cold atom systems; although the conference will also review photonic and solid-state based systems.

By gathering the quantum information and cold atoms communities, this conference will enable participants to exchange on state-of-the-art developments in the vast and active filed of quantum state manipulation.

For more details, visit the conference website:
http://quantumgdr2014.sciencesconf.org/

1.2 Quantum Information: Foundations & Applications

The **GDR - IQFA** (GDR 3322 of the CNRS) is a research network supported by the CNRS Institute of Physique (INP) and the Institute of System and Engineering (INSIS) with which the quantum information community is mostly associated. This network gathers more than 80 research teams from more than 50 research laboratories in France.

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

The **main actions of the GDR - IQFA** can be summarized as follows:

- the will to create strong bridges between the various thematics dealing with quantum information;
- the will to establish a shared knowledge basis through pedagogical tutorials during each of the GDR workshops.
- the promotion of foundations & applications of Quantum Information through a research network aimed at facilitating the emergence of new projects which meet the current and future challenges of the field.

The GDR - IQFA is organized along **eight identified thematics referred to as ARTs**[2] that are currently the subject of intensive research all around the world:

- Coherent manipulation of qubits - CMQ;
- Quantum communication - QCOM;
- Entanglement and non classical states - ENS;
- Quantum simulation and processing - QSP;
- Quantum metrology - QMET;
- Quantum information storage - QIS;
- New qubit devices - NQD;
- Foundations of quantum information - FOUND.

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

[1] Centre National pour la Recherche Scientifique: http://www.cnrs.fr/
[2] Axes de Recherche Thématiques

1.3 Cold atoms

The **GDR - Cold Atoms** (GDR 3577 of the CNRS) is a research network supported by the CNRS *Institut de Physique* (INP). This network gathers researchers from 25 research laboratories accross France.

The goal of the GDR is to strengthen the french research community working on cold atoms. It is organized around **six research themes**:

- Ultracold quantum matter (A. Minguzzi, F. Chevy, B. Laburthe- Tolra, D. Petrov)
- Matter and light waves: quantum coherence and disorder (L. Sanchez-Palencia, G. Labeyrie)
- Quantum optics and information (L. Guidoni, A. Browaeys)
- Metrology and basic measurements (A. Landragin, P. Cladé)
- Relation with other research fields (E. Giacobino, D. Guéry-Odelin, D. Comparat, J. Barré)
- Training & outreach (H. Perrin, Ph. Verkerk, M. Leduc)

For more details, visit the **GDR - Cold Atoms** website:
http://gdr-atomesfroids.cnrs.fr/

1.4 Organization of the conference

This conference is mainly organized by the **Centre Blaise Pascal (CBP)**[3] at the Ecole Normale Supérieure de Lyon (ENS Lyon)[4]. The scientific and logistic coordination is performed by a local committee involving researchers from the Physics and Computer Science Laboratories from the ENS Lyon, as well as researchers from the Université Claude Bernard in Lyon and from laboratories in Grenoble.

On the scientific side, the main goal of this conference is to gather all the various communities working in Quantum Information with Cold Atoms, and to permit to exchange on the recent advances in the field during three days. The conference will rely on 3 communication modes:

- **7 tutorial talks**, having a clear pedagogical purpose, on the very foundations and most advanced applications of the field;
- **16 contributed talks** on the current hot topics within the strategic thematics identified by the GDR - IQFA ARTs.
- and **2 poster sessions** gathering 57 posters, again within the strategic thematics identified by the GDR - IQFA ARTs.

Moreover, an **outreach event** has been organized in order to present an overview of the field to a broader audience, including students from Lyon universities and schools. In the conference's colloquium, **Pr. Jean Dalibard (Collège de France)** will present a synthetic view of recent progresses and perspectives opened by the use of cold atom systems in the field of quantum information, quantum simulation and metrology.

We wish all participants a fruitful conference.

Sébastien Tanzili
Head of the GDR - IQFA
On behalf of the board of the GDR - IQFA

Robin Kaiser
Head of the GDR - Cold Atoms
On behalf of the board of the GDR - Cold Atoms

Pascal Degiovanni & Tommaso Roscilde (Physics Laboratory of the ENS Lyon)
Scientific coordinators of the conference
On behalf of the local organization committee

[3] http://www.cbp.ens-lyon.fr/
[4] http://www.ens-lyon.eu/

2 Venue

The conference will take place at the **Ecole Normale Supérieure de Lyon**. All tutorials and contributed talks as well as Jean Dalibard's colloquium will take place in the "**Amphitheater Charles Mérieux**" which is located on Place des Pavillons, Lyon 7^{me}. The amphitheatre has a capacity for an audience of 511 people. Posters will be displayed in the Atrium of the amphitheater.

Registration

Registration of the participants will start on Monday November 17^{th} at 9:00 am in the Atrium. The opening of the conference is scheduled at 9:30 am and the first talk at 10:00 am.

Lunches

All lunches and coffee breaks during the conference will be delivered on site. Lunches are free of charges for all registered participants.

Conference dinner

The conference dinner will take place at the restaurant **Le Caro de Lyon**[5] in Lyon city center (25 Rue du Bât d'argent - 69001 Lyon - 04 78 39 58 58). The restaurant is close to the subway station Hotel de Ville - Louis Pradel: to go there from the ENS Lyon, take the tramway at the Debourg station, then change for the subway (line A) at the Perrache station.

The dinner will take place on Tuesday, November 18^{th} at 8:30 pm. It is free of charge for people who have mentioned their participation at the early registration stage.

The Ecole Normale Supérieure de Lyon

The **Ecole Normale Supérieure de Lyon**[6] is a recent institution which has inherited a long tradition. At its creation in 2010, it brought together, within a single institution, every subject at the exception of medecine and law to fulfill the traditional missions of training, research and diffusion of knowledge through the implementation of three strategic axis: interdisciplnarity, internationalization and interaction with society.

Research at the ENS Lyon encourages exchanges between subject areas and cultures. It is based on partnerships with the CNRS, INSERM, INRA, INRIA, as well as 260 international partnerships. The ENS Lyon has created structures specifically destined to host projects involving both visiting and permanent researchers. It also actively participates in the Collegium de Lyon which accommodates high level researchers with the aim of creating an international academic community on the campus.

The ENS Lyon gathers 2100 students, 400 PhD students, 700 professors and researchers and 390 administrative and technical staff from more than 60 nationalities on its two campuses. Its total budget is more than 110 M€. It is involved in more than 200 international partnerships and is part of the University of Lyon[7], the second scientific pole in France gathering universities and schools from Lyon and Saint-Etienne.

Transportation

Lyon has a strongly developped public transportation system called **TCL** which includes 4 subway lines, 2 cable train lines, 5 tramway lines, a fast tramway connecting directly to the Lyon Saint Exupéry international airport and many bus lines. The transportation system closes around midnight and opens at 5:00 am. We recommend you to buy a 10-ticket set and share it with people you know to lower the cost.

To have access to the related i maps, schedules and travel planner, please visit the transportation system website:
http://www.tcl.fr/en

[5] http://lecarodelyon.com/
[6] http://www.ens-lyon.eu/
[7] http://www.universite-lyon.fr/

3 Organization & financial supports

This colloquium is organized by:	the GDRs IQFA and Cold Atoms,
with the help of:	the Centre Blaise Pascal (ENS Lyon), the Laboratoire de Physique (ENS Lyon);
the logistic support of:	the Ecole Normale Supérieure de Lyon, the Faculté des Sciences et Technologies (UCBL, Lyon);
and with the financial supports of:	the CNRS, through the Insitutes INP & INSIS, the Laboratoire de Physique (ENS Lyon), the Laboratoire d'Informatique du Parallélisme (ENS Lyon), the Fédération de Recherche André-Marie Ampère (Lyon), ID Quantique S.A. (Switzerland)., *that are warmly acknowledged.*

4 GDR - IQFA, Cold Atoms & Conference Committees

The scientific commitee of the conference is the fusion of the boards of the two research networks (GDRs).

4.1 Board of the GDR - IQFA

Members:	Alexia Auffèves (Institut Néel, UPR 2940, Grenoble), Pablo Arrighi (LIG, UMR 5217, Grenoble), Antoine Browaeys (LCFIO, UMR 8501, Palaiseau), Thierry Chanelière (Lab. Aimé Cotton, UPR 3321, Orsay), Pascal Degiovanni (Lab. Physique de l'ENS Lyon, UMR 5672), Eleni Diamanti (LTCI, UMR 5141, Paris), Iordanis Kerenidis (LIAFA, UMR 7089, Paris), Tristan Meunier (Institut Néel, UPR 2940, Grenoble), Perola Milman (Lab. MPQ, UMR 7162, Paris), Sébastien Tanzilli (Head, LPMC, UMR 7336, Nice), Nicolas Treps (Secretary, LKB, UMR 8552, Paris),
Administration manager:	Nathalie Koulechoff (LPMC, UMR 7336, Nice).

4.2 Board of the GDR - Cold Atoms

Members:	Jean-Claude Garreau (PhLAM, UMR 8523, Lille) Robin Kaiser (Head, INLN, UMR 7335, Nice) Tommaso Roscilde (Lab. de Physique ENS Lyon, UMR 5672, Lyon) Jakob Reichel (LKB, UMR 8552, Paris)

4.3 Local organization committee

Scientific coordinators:	P. Degiovanni (Laboratoire de Physique, ENS Lyon, UMR 5672, Lyon), T. Roscilde, (Laboratoire de Physique, ENS Lyon, UMR 5672, Lyon);
Logistic coordination:	S. Barendson (Centre Blaise Pascal, Lyon);
Members:	Natacha Portier (LIP, ENS Lyon, UMR 5668, Lyon), Pablo Arrighi (LIG, UJF, UMR 5217, Grenoble), Fabrice Vallée (Institut Lumière Matière, UCBL, UMR 5306, Lyon);
with the help of:	S. Tanzilli (LPMC, UMR 7336, Nice), N. Clervaux (Laboratoire de Physique, UMR 5672, ENS Lyon), L. Mauduit (Laboratoiren de Physique, UMR 5672, ENS Lyon);
Staff:	C. Cabart (Laboratoire Pierre Aigrain, ENS Paris), A. Feller (Labo de Physique, UMR 5672, ENS Lyon), I. Frérot (Labo de Physique, UMR 5672, ENS Lyon), B. Roussel (Labo de Physique, UMR 5672, ENS Lyon), E. Thibierge (Labo de Physique, UMR 5672, ENS Lyon), N. Tremblay (Labo de Physique, UMR 5672, ENS Lyon);
with the help of:	B. Sebire (Amphitheatre technical control, ENS Lyon).

5 Tutorials and Colloquium

The tutorials and the Colloquium will appear according to the conference schedule:

- **Monday 17th, 11:00 – 12:00**: *Quantum annealing and quantum simulation* - Prof. Dr. Mathias Troyer (Inst. for Theoretische Physik, ETH Zürich);
- **Monday 17th, 15:30 – 16:30**: *Electron and nuclear spin qubits using donors in silicon.* - Prof. John Morton (University College London & London center for Nanotechnology);
- **Monday 17th, 18:10 – 19:10**: *Ultra-cold gases: a quantum world at the interface between atomic and condensed matter physics* - Prof. Jean Dalibard (Collège de France);
- **Tuesday 18th, 9:00 – 10:00**: *Quantum walks with neutral atoms* – Prof. Dr. Dieter Meschede (Bonn University);
- **Tuesday 18th, 14:00 – 15:00**: *Magnetism without magnetism: Physics with ultracold quantum gases* – Prof. Dr. Klaus Sengstock (Hamburg University);
- **Tuesday 18th, 16:30 – 17:30**: *Using the Wigner function to calculate expectation values* – Prof. Dr. Gerd Leuchs (University of Erlangen & Mac Planck Institute for the Science of Light)
- **Wednesday 19th, 9:00 – 10:00**: *Causal relations in a quantum world*, Dr. Cyril Branciard (CNRS, Institut Néel, Grenoble)
- **Wednesday 19th, 14:00 – 15:00**: *Electron quantum optics* – Pr. Gwendal Fève (Université P. & M. Curie and Laboratoire Puierre Aigrain, ENS Paris)

Quantum annealing and quantum simulation

Matthias Troyer
Institut f. Theoretische Physik, ETH Zürich, Wolfgang-Pauli-Str. 27, 8093 Zürich - Switzerland

Using the quantum adiabatic approach one can bring a quantum system from an easy to prepare state towards the ground state of a complex system. It can be used both to solve classical optimization problems in a quantum annealer, when the final Hamiltonian is a classical model representing the optimization problem. Alternatively it can be used as a quantum simulator to find low energy states of quantum models. I will discuss both approaches in the context of superconducting qubit devices and ultracold atomic gases. I will assess their potential and limitations and will draw analogies to the history of classical computing.

Electron and nuclear spin qubits based on donors in silicon

G. Wolfowicz[1,2], M. Urdampilleta[1], C.C. Lo[1,3], H. Riemann[4], N.V. Abrosimov[4], P. Becker[5], H.-J. Pohl[6], M.L.W. Thewalt[7], A.M. Tyryshkin[8], S.A. Lyon[8], J.J.L. Morton[1,3]
[1]*London Centre for Nanotechnology, London WC1H 0AH, UK*
[2]*Dept. of Materials, Oxford University, Oxford OX1 3PH, UK*
[3]*University College London, London WC1E 7JE, UK*
[4]*Inst. for Crystal Growth, D-12489 Berlin, Germany*
[5]*Physikalisch-Tech., D-38116 Braunschweig, Germany*
[6]*Vitcon Projectconsult GmbH, 07745 Jena, Germany*
[7]*Simon Fraser University, Burnaby, V5A 1S6, Canada*
[8]*Princeton University, New Jersey 08544, USA*

Electron and nuclear spins of donors in silicon are promising candidates for representing quantum bits, with coherence times of up to 3 seconds for the electron spin[1] up to 3 minutes for the neutral donor nuclear spin[2], and 3 hours for the ionized donor nuclear spin[3]. Furthermore, single-shot readout of both the electron spin and nuclear spin have been demonstrated, with measurement fidelities of up to 99.8%[4, 5]. In order to scale up to more complex quantum devices based on donors, it is necessary to find a way to coherently control individual spins (or at least a defined subset of them) within a larger array. One approach is to apply global microwave fields to coherently excite resonant spins, combined with (pulsed) DC electric fields to bring different spins in or out of resonance with the control field, using the Stark shift. We present Stark shift data for all group-V donors in silicon (P, As, Sb and Bi), and show how electric fields can be used for conditional control of nuclear spins[6]. An alternative method is to apply local AC electric fields, which we show theoretically can be used to drive spin transitions in certain regimes through modulation of the hyperfine coupling.

[1] G. Wolfowicz *et al.*, Nature Nanotechnology **8** 561 (2013).
[2] M. Steger *et al.*, Science **336** 6086 (2012).
[3] K Saeedi *et al.*, Science **342** 830 (2013).
[4] J. J. Pla *et al.*, Nature **489** 541 (2012).
[5] J. J. Pla *et al.*, Nature **496** 334 (2012).
[6] G. Wolfowicz *et al.*, Phys. Rev. Lett **113** 157601 (2014).

Les gaz ultra-froids : un monde quantique entre physique atomique et matière condensée

Jean Dalibard*
Collège de France, Laboratoire Kastler Brossel, 11 Place Marcelin Berthelot, 75005 Paris

Faire du froid à partir de lumière ? Au cours des 20 dernières années, ce but pour le moins paradoxal a été atteint dans les laboratoires de physique atomique avec des performances dépassant les prévisions les plus optimistes. Des faisceaux lumineux bien choisis permettent d'amener une assemblée d'atomes à une température située quelques nanokelvins seulement au dessus du zéro absolu.

Le comportement des gaz ainsi obtenus est gouverné par la mécanique quantique : la vitesse des particules est fortement diminuée et leur longueur d'onde augmentée, ce qui permet la réalisation d'horloges et de capteurs interférométriques (accélération, rotation) d'une précision inégalée. Par ailleurs, en concentrant ces atomes en un petit volume, on réalise une « matière quantique » qui constitue un simulateur de systèmes encore mal compris, comme le fluide d'électrons dans un matériau supraconducteur ou dans un solide à effet Hall quantique.

L'exposé présentera brièvement les principes à la base du refroidissement. Il décrira ensuite quelques développements récents, à la fois sur le plan des mesures de précision « à un atome » et sur celui des phénomènes collectifs en lien avec la physique de la matière condensée. Il se terminera par un bref panorama des perspectives de ce domaine de recherche.

Ultra-cold gases : a quantum world at the interface between atomic and condensed matter physics

Freezing matter with light ? During the two last decades, this rather paradoxical goal has been reached in atomic physics labs, with performances that overpassed the most optimistic initial predictions. Well chosen laser beams can bring an atomic assembly to a temperature only a few nanokelvins above the absolute zero.

The behavior of these gases is governed by Quantum Mechanics. The velocities of the particles are strongly decreased and their wavelength increased, which allows for the realization of clocks and interferometric sensors (acceleration, rotation) with an unprecedented precision. By concentrating these atoms in a small volume, one produces a "quantum matter" that may constitute the basis of a simulator for other systems that are still not fully understood, such as the electronic fluid in a superconductor or in a Quantum Hall device.

The talk will briefly present the physical principles at the basis of the cooling. It will then describe a few recent developments, dealing either with single-atom-based precision measurements or collective phenomena in relation with condensed matter physics. It will end up with a brief panorama of the perspectives open in this research field.

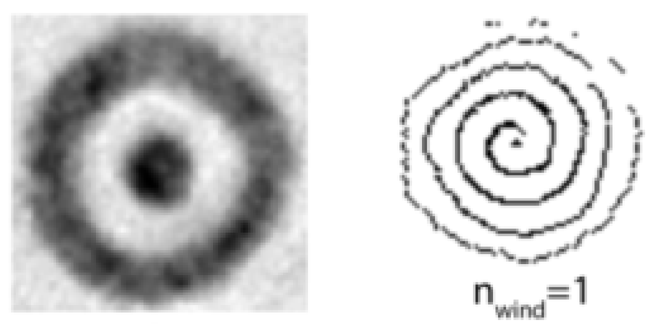

FIGURE 1. Un exemple de circuiterie à atomes. (i) A gauche, un piège pour atomes formé par une zone centrale et un anneau. (ii) A droite, figure d'interférence obtenue en laissant se recouvrir les deux composantes de l'image de gauche. Cette spirale révèle la présence d'un courant permanent dans l'anneau [photo extraite de L. Corman et al., Phys. Rev. Lett. **113**, 135302 (2014)].

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Quantum walks with neutral atoms

Dieter Meschede
Institut für Angewandte Physik, Universität Bonn, Wegelerstr. 8, D-53115 Bonn - Germany

Cold atoms undergoing quantum walks in a deep optical lattice are coherently delocalized on a very large Hilbert space lattice. With electric quantum walks of single atoms transport phenomena including spin orbit coupling, Bloch oscillations or Anderson like localization are realized in a single experiment. Physical insight into the ?quantumness ? of the system is obtained by an analysis of decoherence phenomena and non-invasive measurements. Controlled interaction of exactly two quantum walkers remain a daunting but highly attractive experimental challenge.

Magnetism with and without magnetism : Different regimes of magnetic interactions in quantum gases

Klaus Sengstock
Institut für laserphysik, University of Hamburg

The talk will address different regimes of magnetic interactions in ultracold quantum gases. The spin dependent contact interaction of ultracold atoms can lead to surprising collective behavior of e.g. fermionic atoms in optical lattices and in bulk [1, 2]. Recently artifcial gauge fields even allowed to study magnetic like interactions for completely non-magnetic atoms [3, 4] and to simulate strong external magnetic fields which eventually allow to realize high-B-field physics like the Hofstadter butterfly.

[1] Krauser *et al*, Nature Physics **8**, 813 (2012).
[2] Krauser *et al*, Science **343**, 157 (2014).
[3] Struck *et al*, Science **333**, 996 (2011).
[4] Struck *et al*, Nature Physics **9**, 738 (2013).

Using the Wigner function to calculate expectation values

Gerd Leuchs[1,2,3], Birgit Stiller[1,2]
[1]Max Planck Institute for the Science of Light, Erlangen, Germany
[2]Department of Physics, University Erlangen-Nürnberg, Germany
[3]Department of Physics, University of Ottawa, Canada

The quantum state of a light mode can be described in different ways, one way is by the Wigner function of the state. This representation is effectively a continuous variable decription and has the advantage of describing both pure and mixed states. Using the Wigner function of a state it is straight forward to predict the outcome of homodyne measurements, because the field operators composing the corresponding measurement operator are symmetrically ordered and the Wigner function likewise corresponds to symmetric ordering. Other measurements may be described by operators in which the field operators are normally or anti-normally ordered. Direct detection e.g. corresponds to normal ordering and eight port homodyning to anti-normal ordering. In these cases the transition from one type of ordering to another has to be taken into account.

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[1] B. Stiller, U. Seyfarth, and G. Leuchs, "Temporal and spectral properties of quantum light", Les Houches lectures 2013, arXiv:1411.xxxx

Causal relations in a quantum world

Cyril Branciard*
Institut Néel, CNRS, 38042 Grenoble Cedex 9, France

Quantum theory radically changes the way we perceive and understand the physical world. One of the concepts that needs to be revisited is that of causality. In this talk I will discuss two questions related to the notion of causality in the quantum realm, which are currently the subject of active research. First, I will discuss how the violation of Bell inequalities (i.e. of Bell's assumption of "local causality") challenges our classical understanding of causality, and which causal structures can underly nonlocal correlations. Second, I will present a possible approach to the study of quantum correlations with indefinite causal structure—allowing for some form of "superposition" of causal orders (i.e. of "A causes B" and "B causes A").

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Electron quantum optics in ballistic chiral conductors

Gwendal Fève
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The ballistic propagation of electronic waves along the quantum Hall edge channels of a two dimensional electron gas bears strong analogies with photon optics. Ballistic and one-dimensional propagation are ensured by the chiral quantum Hall edge states and electronic beam splitters can be implemented using quantum point contacts. These analogies have inspired a whole set of experiments, including the realization of electronic Mach-Zehnder [1] and Hanbury-Brown & Twiss [2] interferometers, providing an efficient tool to understand both the wave and corpuscular nature of electronic propagation in quantum conductors. However, fundamental differences with photon optics remain [3] : firstly from the presence of the Fermi sea and secondly from the Coulomb interaction between electrons. Using single electron emitters [4], these analogies and differences can now be probed down to the single particle scale which proves particularly efficient to test the limits of the single particle description and the emergence of many body physics [4].

[1] Ji *et al*, Nature **422**, 415 (2003)
[2] Henny *et al*, Science **284**, 296 (1999).
[3] E. Bocquillon, V. Freulon, F.D. Parmentier, J.-M. Berroir, B. Plaçais, C. Wahl, J. Rech, T. Jonckheere, T. Martin, C. Grenier, D. Ferraro, P. Degiovanni and G. Fève, Annalen der Physik (Berlin), **526** , 1 (2014).
[4] G. Fève, V. Freulon, J.-M. Berroir, P. Degiovanni, B. Plaçais, A. Cavanna, Y. Jin and G. Fève, Science **316**, 1169 (2007).
[5] D. Ferraro, B. Roussel, C. Cabart, E. Thibierge, G. Fève, C. Grenier and P. Degiovanni, Phys. Rev. Lett. **113**, 166403 (2014).

6 Abstracts of the talks and posters

In the following, you can find all the contributions given per ART. The contributed talks are organized according to the ARTs. An author index is provided at the end of the book.

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Coherent manipulation of qubits - CMQ

Correlations of microwave photons emitted by inelastic Cooper pair tunneling

Alexander Grimm[1,2], Salha Jebari[1,2], Dibyendu Hazra[1,2], Carles Altimiras[3], Olivier Parlavecchio[3], Fabien Portier[3] and Max Hofheinz[1,2*]
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A simple DC voltage-bias on a small Josephson junction leads to emission of microwave radiation via inelastic Cooper-pair tunneling. In this process a tunneling Cooper pair emits one or several microwave photons with a total energy of 2eV [1]. The observed average photon emission rate is well explained within the so-called P(E) theory [2], but this theory does not make any predictions about the statistics of the emitted photons.

I will present experiments showing that these statistics can be highly nontrivial, in agreement with recent theory [3–5]. Depending on the bias conditions and the impedance of the circuit in which the junction is embedded, correlations can range from strongly bunched to anti-bunched.

This type of devices might therefore offer a new way of generating useful photon states for circuit quantum optics experiments, without the need of carefully calibrated control pulses. Moreover, the frequency of the emitted radiation is only limited by the gap of the superconductor. We are building our devices using NbN-MgO-NbN tunnel junctions which should in principle allow operation up to the THz regime.

[1] M. Hofheinz et al., "Bright Side of the Coulomb Blockade", PRL **106**, 217005 (2011).
[2] G.-L. Ingold and Y.V. Nazarov, in "Single Charge Tunneling, edited by H. Grabert and M.H. Devoret" (Plenum, New York, 1992).
[3] C. Padurariu et al., "Statistics of radiation at Josephson parametric resonance" PRB **86**, 054514 (2012).
[4] V. Gramich et al., "From Coulomb-Blockade to Nonlinear Quantum Dynamics in a Superconducting Circuit with a Resonator" PRL **111**, 247002 (2013).
[5] J. Leppäkangas et al., "Input-output description of microwave radiation in the dynamical Coulomb blockade " NJP **16**, 015015 (2014).

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Multiplexed control and single-shot readout of transmon qubits

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After having demonstrated quantum speedup with a very simple 2 qubit superconducting processor [1], our group is developing a more scalable multi-qubit architecture. As a first step, we have fabricated and tested a 4 transmon qubit circuit (see figure), each fitted with a Josephson bifurcation amplifier (JBA) for single-shot qubit readout [2]. All qubit cells are coupled to a single transmission line carrying all the qubit drive and readout signals. We demonstrate the simultaneous measurement of Rabi oscillations of the four transmons.

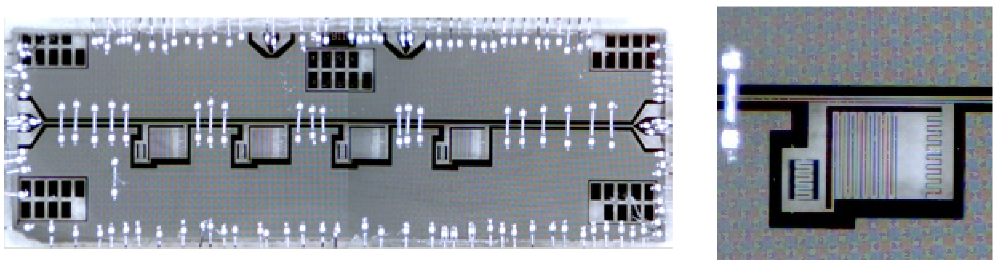

FIGURE 1. (Left) 4 transmon qubit-readout resonator cells coupled to a common transmission line carrying qubit drive and readout signals. (Right) Transmon qubit (on the left) capacitively coupled to a non-linear resonator (on the right) for readout

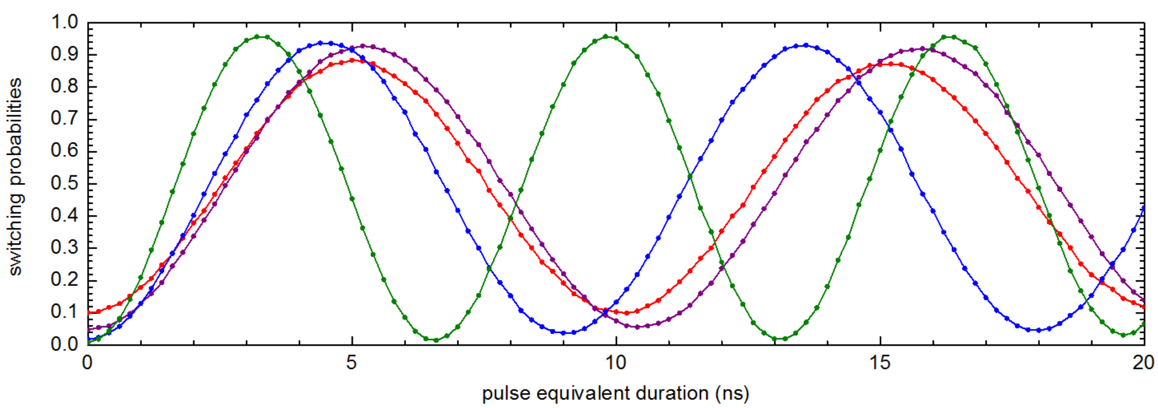

FIGURE 2. Multiplexed simultanous Rabi oscilations of 4 qubits

[1] A. Dewes, R. Lauro, F. R. Ong, V. Schmitt, P. Milman, P. Bertet, D. Vion, and D. Esteve, "Quantum speeding-up of computation demonstrated in a superconducting two-qubit processor" Phys. Rev. B 85, 140503(R) (2012)

[2] F. Mallet, FR. Ong, A. Palacios-Laloy, F. Nguyen, P. Bertet, D. Vion, and D. Esteve, "Single-shot qubit readout in circuit quantum electrodynamics", Nature Phys. 5, 791 (2009)

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Long coherence times for Rydberg qubits on a superconducting atom chip

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Rydberg atoms are the focus of a thriving experimental and theoretical activity. Many proposals for quantum simulation of condensed matter systems and quantum information processing exploit their strong, long-range, dipole interaction. Exciting Rydberg atoms in a BEC prepared on a superconducting atom chip [1], is particularly promising in this context. It opens the route to a hybrid interface between on-chip quantum superconducting circuits and atomic ensembles.

Manipulating Rydberg atoms with an atom chip, however, requires a good control of electric field nearby a metallic surface, as highly excited atoms are very sensitive to Stark effect. The problem is more crucial as soon as there is formation of dipolar patches due to uncontrolled Rb deposition on the chip surface [2–5]. A simple solution for our particular experiment with superconducting atom chip consists in covering all essential metallic surfaces by a layer of Rb. Thanks to that we could demonstrate unprecedented long coherent manipulation for transition between adjacent Rydberg levels with principal quantum number $n \approx 60$, by using standard microwave spectroscopy techniques (Rabi oscillation, Ramsey interference and spin echo). The measured coherence time is in the ms range, exceeding the lifetime of Rydberg atoms themselves [6]. This reveals new perspectives for studying the collective excitation dynamics of ultra cold atomic ensemble in the strong dipole blockade regime.

[1] C. Roux, A. Emmert, A. Lupascu, T. Nirrengarten, G. Nogues, M. Brune, J.-M. Raimond, and S. Haroche, EPL **81**, 56004 (2008).
[2] J. D. Carter and J. D. D. Martin, Phys. Rev. A **83**, 032902 (2011).
[3] L. A. Jones, J. D. Carter, and J. D. D. Martin, Phys. Rev. A **87**, 023423 (2013).
[4] A. Tauschinsky, R. M. T. Thijssen, S. Whitlock, H. B. van Linden van den Heuvell, and R. J. C. Spreeuw, Phys. Rev. A **81**, 063411 (2010).
[5] R. P. Abel, C. Carr, U. Krohn, and C. S. Adams, Phys. Rev. A **84**, 023408 (2011).
[6] Arxiv XXX

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“New types of qubits - NQD”

Electrical manipulation of a single nuclear spin

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Breakthroughs in addressing isolated nuclear spins has opened up a path towards nuclear spin based quantum bits [1], which benefit from long coherence times due to their inherent environmental isolation. To coherently manipulate the state of the nuclear spin, local magnetic fields, generated by on-chip coils, are employed [2]. However, performing this quantum manipulation electrically would have several advantages. Besides a tremendous reduction of Joule heating, electric fields allow for fast switching and spatially confined spin control. In this work, we proposed and demonstrated the coherent single nuclear spin manipulation using electric fields only [3]. To perform our experiments, we used a three terminal nuclear spin qubit transistor [4]. The transistor, consisting of a TbPc2 single-molecule magnet coupled to source, drain, and gate electrodes, was studied by performing electrical transport measurements inside a dilution refrigerator at 40 mK.

Since there is no direct coupling between the spin and the electric field, we make use of the hyperfine Stark effect as a magnetic field transducer at the atomic level. This quantum mechanical process is present in all nuclear spin system, such as P or Bi atoms in Si, and offers a general route towards the electrical control of nuclear spin based devices.

[1] B. E. Kane, A silicon-based nuclear spin quantum computer. Nature **393**, 133-137 (1998).
[2] J. J. Pla, K. Y. Tan, J. P. Dehollain, W. H. Lim, J. J. L. Morton, F. Zwanenburg, D. N. Jamieson, A. S. Dzurak and A. Morello, High-fidelity readout and control of a nuclear spin qubit in silicon. Nature **496**, 334-8 (2013).
[3] S. Thiele, F. Balestro, R. Ballou, S. Klyatskaya, M. Ruben and W. Wernsdorfer, Electrically driven nuclear spin resonance in single-molecule magnets. Science **344**, 1135 (2014).
[4] R. Vincent, S. Klyatskaya, M. Ruben, W. Wernsdorfer and F. Balestro, Electronic read-out of a single nuclear spin using a molecular spin transistor. Nature **488**, 357-360 (2012).

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Experimental Boson Sampling with integrated photonics

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Integrated photonic circuits have a strong potential to perform quantum information processing [1, 2]. Indeed, the ability to manipulate quantums states of light by integrated devices may open new perspectives both for fundamental tests of quantum mechanics and for novel technological applications [3, 4]. Within this framework we have developed a directional coupler, fabricated by femtosecond laser waveguide writing, acting as an integrated beam splitter able to support polarization-encoded qubits [5]. As following step we addressed the implementation of quantum walk. This represents one of the most promising resources for the simulation of physical quantum systems, and has also emerged as an alternative to the standard circuit model for quantum computing. Up to now the experimental implementations have been restricted to single particle quantum walk, while very recently the quantum walks of two identical photons have been reported. For the first time, we investigated how the particle statistics, either bosonic or fermionic, influences a two-particle discrete quantum walk [6]. Such experiment has been realized by adopting two-photon entangled states and integrated photonic circuits. As following step we have exploited this technology to simulate the evolution for disordered quantum systems observing how the particle statistics influences Anderson localization. Finally we will discuss the perspectives of optical quantum simulation : the implementation of the boson sampling to demonstrate the computational capability of quantum systems [7, 8] and the development of integrated architecture with three-dimensional geometries [9, 10].

[1] T. D. Ladd, et al, Quantum computers, *Nature* 464, 45Ð53 (2010).
[2] J. L. O Brien, A. Furusawa, and J. Vuckovic, Photonic quantum technologies, *Nature Photonics* 3, 687 (2009).
[3] P. Kok, et al, Linear optical quantum computing with photonic qubits, *Rev. Mod. Phys.* 79, 135 (2007).
[4] A. Politi, J. Matthews, M. Thompson, and J.O Brien, Integrated quantum photonics, Selected Topics in Quantum Electronics, *IEEE Journal of QE* 1673, 15 (2009).
[5] L. Sansoni, F. Sciarrino, G. Vallone, P. Mataloni, A. Crespi, R. Ramponi, R. Osellame, Polarization entangled state measurement on a chip, *Phys. Rev. Lett.* 105, 200503 (2010).
[6] L. Sansoni, F. Sciarrino, G. Vallone, P. Mataloni, A. Crespi, R. Ramponi, R. Osellame, Two-particle bosonic-fermionic quantum walk via 3D integrated photonics, *Phys. Rev. Lett.* 108, 010502 (2012) ; A. Crespi, R. Osellame, R. Ramponi, V. Giovannetti, R. Fazio, L. Sansoni, F. De Nicola, F. Sciarrino, and P. Mataloni, Anderson localization of entangled photons in an integrated quantum walk, *Nature Photonics* 7, 322 (2013).
[7] A. Crespi, R. Osellame, R. Ramponi, D. J. Brod, E. F. Galvao, N. Spagnolo, C. Vitelli, E. Maiorino, P. Mataloni, and F. Sciarrino, Experimental boson sampling in arbitrary integrated photonic circuits, *Nature Photonics* 7, 545 (2013).
[8] N. Spagnolo, C. Vitelli, M. Bentivegna, D. J. Brod, A. Crespi, F. Flamini, S. Giacomini, G. Milani, R. Ramponi, P. Mataloni, R. Osellame, E. F. Galvao, F. Sciarrino, Experimental validation of photonic boson sampling, *Nature Photonics* 8, 615 (2014).
[9] N. Spagnolo, C. Vitelli, L. Aparo, P. Mataloni, F. Sciarrino, A. Crespi, R. Ramponi, and R. Osellame, Three-photon bosonic coalescence in an integrated tritter, *Nature Communications* 4, 1606 (2013).
[10] N. Spagnolo, L. Aparo, C. Vitelli, A. Crespi, R. Ramponi, R. Osellame, P. Mataloni, and F. Sciarrino, Quantum interferometry with three-dimensional geometry, *Sci. Rep.* 2, 862 (2012).

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Entanglement and non-classical states - ENS

Creation and tomography of entangled states in an atomic ensemble using an optical cavity

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Multiparticle entanglement enables quantum simulations, quantum computing and quantum-enhanced metrology. Yet, there are few methods to produce and measure such entanglement while maintaining single-qubit resolution as the number of qubits is scaled up. Using atom chips and fiber-optical cavities [1], we have developed two methods to create symmetric entangled states of atoms, in particular the W state, independently of the atom number. Both methods are based on a non-destructive collective measurement of the atoms by the cavity. In our experiment, we demonstrate creation and analysis of entangled states with mean atom numbers up to 41. The presence of multi-particle entanglement is assessed using a specifically developed criterion that detects entangled states in the vicinity of the W state.

The first method relies on conditional evolution upon the result of the non-destructive measurement and can be seen as a primitive form of quantum feedback [2]. In the second method, we combine unitary evolution with continuous measurement [3]. The resulting dynamics is an example of Quantum Zeno Dynamics, during which the evolution is restricted to a subspace of the Hilbert space therefore producing entanglement.

[1] D. Hunger, T. Steinmetz, Y. Colombe, C. Deutsch, T.W. Hänsch, and J. Reichel, "A fiber Fabry-Perot cavity with high finesse", New Journal of Physics **12**, 065038 (2010).

[2] F. Haas, J. Volz, R. Gehr, J. Reichel, and J. Estève, "Entangled States of More Than 40 Atoms in an Optical Fiber Cavity", Science **344**, 180-183 (2014).

[3] G. Barontini, L. Hohmann, F. Haas, J. Estève, and J. Reichel, "Deterministic Generation of Multiparticle Entanglement by Quantum Zeno Dynamics", submitted.

Time-division demultiplexing for polarization-entangled photons

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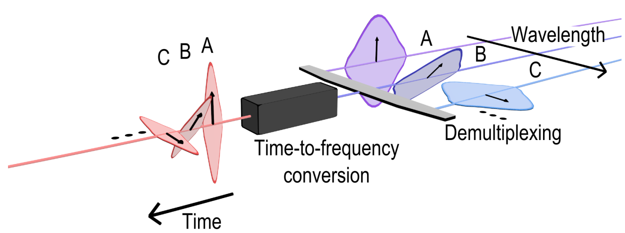
Due to their high speed and low decoherence, photons are the ideal carrier of quantum information in quantum communications networks. Physical transmission channels, such as fiber-optic cable, are well established resources from classical optical telecommunications. To efficiently use these resources, it is necessary to multiplex many photonic signals into different channels on the same transmission line.

In particular, one may use the arrival time of single photons to discriminate different channels ; in this application, one is limited by the timing resolution of detection systems, which is generally on the scale of nanoseconds. In principle, one only needs time differences on the order of the photon's coherence time, which may be as small as tens of femtoseconds. Reaching this fundamental timescale would greatly increase the density of information which may be transmitted in a single transmission line.

I want to present a technique and results for reading an ultrafast train of entangled quantum signals, separated in time by only their coherence length. This is based on our previous work on the spectral compression single photons [1]. Our demultiplexing scheme combines tools from ultrafast pulse shaping and strong-field nonlinear optics and applies them to single photons. We demonstrate this technique for a train of three single-photon channels with interchannel separations of only three picoseconds, converting this separation to a wavelength shift compatible with commercial dense wavelength-division multiplexing. Moreover, we explicitly demonstrate that entanglement is preserved throughout our scheme by performing full quantum state tomography, demonstrating our technique's suitability for the distribution of quantum resources.

The convergence of quantum and nonlinear optics is an exciting frontier for rich new physics and powerful applications. Our work is of interest for this conference because it relies on coherent manipulation of entangled photonic states, quantum communication and could even be used in metrology and find applications for quantum memories.



Time-to-frequency conversion concept. A train of temporally narrow polarized photonic signals A-C are converted into a comb of spectrally narrow and correspondingly polarized photons with a central frequency dependent on their time of arrival. The different frequency modes may then be demultiplexed using diffraction techniques.

[1] J. Lavoie, J. M. Donohue, L. G. Wright, A. Fedrizzi, and K. J. Resch, "Spectral compression of single photons", Nature Photonics **7**, 363-366 (2013).

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Self-testing quantum random number generator

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The generation and certification of unpredictable sequences of numbers is a task of paramount importance in modern science, e.g. for implementation of classical or quantum cryptography protocols, but also in simulation algorithms and gambling. High-quality random numbers are hard to produce. All the solutions based on algorithms such as a computer program are perfectly deterministic. Therefore, in the last two decades, an intense research effort has been devoted to extract randomness from quantum systems since they can provide intrinsic randomness. Devices for quantum random number generation (QRNG) are now commercially available. The simplest approach consists in sending single photons on a 50/50 beamsplitter and detecting the output path [1]. Alternatively one can measure the quantum fluctuations of the number of photons impinging on a detector which has high sensitivity [2]. In all these approaches, it is crucial to model the device accurately in order to estimate the entropy of the output sequence. Consequently, all the classical sources of imperfections must be modeled and, if necessary, calibrated. If the properties of the device change during the random-bit generation, the model might no longer be valid, and the entropy could be overestimated.

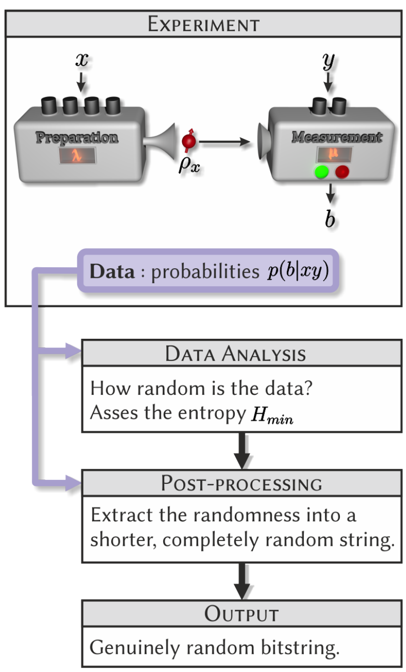

FIGURE 1. Protocol sketch.

In the talk we are going to present a simple, efficient, and practical protocol to create a self-testing QRNG. Our approach requires the exchange of single photons between two separate devices, respectively the preparation and measurement device (see Fig.1). The first device encodes information in the single photons while the measurement device measures it. The encoding and the measurement are made by choosing between two settings which correspond to two incompatible bases. We design a witness able to quantify the incompatibility of the basis using only the statistics of the experimental data and the settings chosen. Then we derive a bound on the min-entropy of the quantum randomness in the output string : therefore we are able to distinguish the quantum randomness from the other sources of randomness due to technical imperfections. The witness only assumes that the two devices act independently and that they exchange single photons. This powerful tool allows to monitor the entropy of the output string while the device is running. Then the extractor can be adapted in order to output a string with a minimal guaranteed randomness.

We implemented the complete QRNG protocol using an heralded single-photon source. The information is encoded in the polarization of the single photons with a setup similar to a BB84 protocol. We also improve the model to consider multi-photon pairs. This requires modelling and calibrating the optical source. This calibration is easier and more reliable than calibrating the measurement device. The proof-of-principle experiment generates 27 bits per second with certified entropy. Our protocol includes the extractor and the finite-size contributions.

[1] A. Stefanov, *et al.*, J. Mod. Opt. **47**, 595 (2000).
[2] B. Sanguinetti, *et al.*, arXiv e-print (2014), arXiv :1405.0435.

Electrically Tunable Bright Sources of Indistinguishable Single Photons

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

Here, we report on the fabrication of electrically tunable, ultrabright sources of indistinguishable single photons. We propose a novel structure design which permits easy implementation of the electrical contacts as well as high brightness. The sample consists of a cavity surrounded by GaAs/AlGaAs Bragg mirrors, doped in the p-i-n diode configuration. In order to apply an electric field to the structure, a 2-3 µm micro-pillar is connected to a larger ohmic-contact surface with four 1D-bridges and a surrounding frame (Fig. 1a). The fundamental cavity mode (CM) of the structure is confined in the centre of the pillar. Deterministic positioning of a single QD at the centre of the connected pillar structure is performed at 4K using an advanced single in-situ optical lithography step (Fig. 1b) [2, 3]. Emission mapping of the final device shows a strong emission from the QD located at the centre of the pillar (Fig. 1c).

A strong Purcell effect is obtained with such a device, which in turn results in a very high brightness of the single-photon source, exceeding 55%. Electrical tuning of the QD transition is possible over a few nm spectral range and can be used to maximize the light-matter interaction by tuning the QD line into resonance with the CM (Fig. 1d). The autocorrelation function at zero delay shows a high single photon-purity of the source with $g^{(2)}(0)=0.01$ (Fig. 1e), and Hong-Ou-Mandel measurements demonstrate mean wavepacket overlaps in the 70-to 80% range (Fig. 1f).

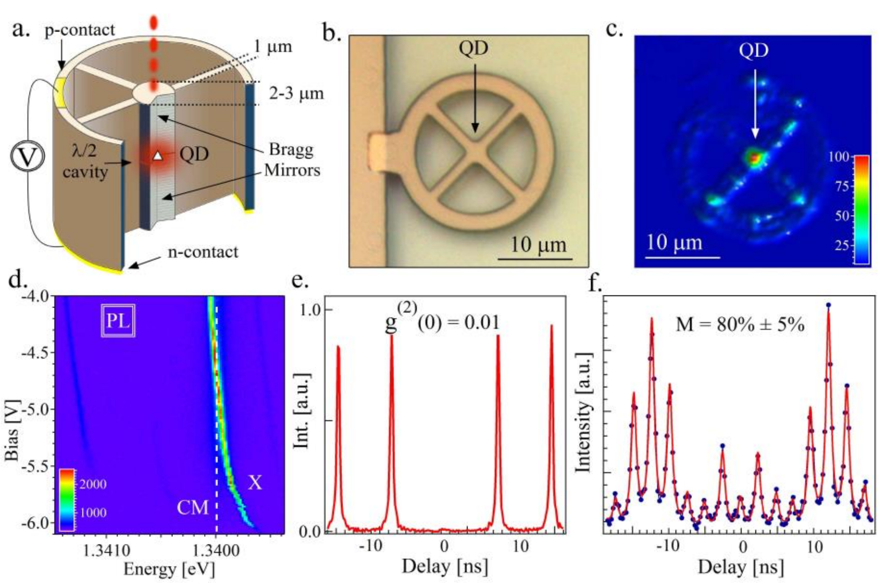

Figure 1: **a)** Schematic of the connected–pillar device fabricated by in-situ lithography. **b, c)** Microscope image and photoluminescence intensity map of the device under study. **d)** PL contour plot recorded at different applied voltage showing the exciton line shift across the cavity mode. **e, f)** Second order autocorrelation function $g^{(2)}(\tau)$ and mean photon overlap M which enlighten high single photon purity and indistinguishability of the source.

[1] O. Gazzano et at., Nat.Comm. 4, 1425 (2013)
[2] A. Dousse et at., Phys. Rev. Lett. 101, 267404 (2008)
[3] A. Nowak et al., Nat.Comm. 5, 3240 (2014).

Quantum Information Storage - QIS

Quantum memory for cylindrical vector beams

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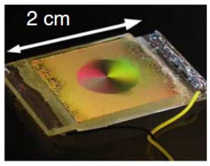

Liquid crystal plates (q-plate) [6]

Like atoms, light presents spin momentum, whose circular polarization is an eigenstate, but can also present orbital angular momentum (OAM) [1]. The latter is associated to a spatial azimuthal variation of some light properties. This can be variation of the optical phase of light. In that case, this degree of freedom can lead to high-density information coding for (quantum) optical communications [2–4]. Recently, It has also been proposed to combine phase-structuring and polarization [5]. These states, which are called cylindrical vector beams, are hybrid spin-orbit momentum states of light and bring many new interesting properties and applications : in the classical world, OAM of light can lead to strong focusing, optical trapping or high sensitivity measurements. In the quantum world, spin-orbit entanglement, high density and alignment-free quantum communications are one of the promising potentialities offered by these vector beams [6, 7]. In the context of quantum communications, vector beams should be compatible with optical quantum memories in order to ensure long-distance transmissions when associated to repeaters. The ability of ensemble-based atomic memories to preserve the spatial coherence and the intensity profile of light make them natural candidates to store these states [3, 4].

We have experimentally demonstrated the possibility to store and reemit on demand these vector beams with a multiplexed quantum memory based on electromagnetic induced transparency in a large ensemble of cold cesium atoms. Vector beams are produced with recently developed spatially-variant liquid crystal plates called q-plate [8]. A storage/retrieval efficiency of 25% has been obtained together with a fidelity of the retrieved states of 96% on average. Measurements have been done with a mean photon number per pulse of 0.5 demonstrating the potentiality of our memory for quantum communications. Moreover, some particular kind of vector beams are rotationally invariant [6]. Using these states as qbits allows quantum communications which are insensitive to any misalignments in rotation between the source and the detection basis. By measuring the fidelity of the reemited vector beams as a function of this misalignment, we verified that our memory protocol keeps the rotationally invariance of these particular vector beams. This demonstration paves the way towards alignement-free long-distance quantum communications with vector beam qbits.

[1] L. Allen, S. Barnett and M. Padgett, "Optical Angular Momentum", IOP publishing, (2003).
[2] J. Leach, M. Padgett, S. Barnett, S. Franke-Arnold, J. Courtial, "Measuring the Orbital Angular Momentum of a Single Photon", Phys. Rev. Lett. **88**, 25 (2002).
[3] A. Nicolas, L. Veissier, L. Giner, E. Giacobino, D. Maxein and J. Laurat, "A quantum memory for orbital angular momentum photonic qubits.", Nature photonics. **8**, 234 (2014).
[4] L. Veissier, A. Nicolas, L. Giner, D. Maxein, A.S. Sheremet, E. Giacobino, J. Laurat, "Reversible optical memory for twisted photons.", Opt. lett. **38**, 712 (2013).
[5] Q. Zhan, "Cylindrical vector beams : from mathematical concepts to applications", Adv. Opt. Photonics **1**, 1 (2009).
[6] V. D'ambrozio, E. Nagali, S.P. Walborn, L. Aolita, S. Slussarenko, L. Marrucci and F. Sciarrino, "Complete experimental toolbox for alignment-free quantum communication", Nature Commun. **3**, 1961 (2012).
[7] V. D'ambrozio, N. Spagnolo, L. Del Re, S. Slussarenko, Y. Li, L.C. Kwek, L. Marrucci, S.P. Walborn, L. Aolita and F. Sciarrino, "Photonic polarization gears for ultra-sensitive angular measurements.", Nature Commun. **4**, 2432 (2013).
[8] L. Marrucci, C. Manzo, D. Paparo, "Optical Spin-to-Orbital Angular Momentum Conversion in Inhomogeneous Anisotropic Media.", Phys. Rev. Lett. **96**, 163905 (2006).

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Quantum simulation and information processing - QSP

Quantum simulation of dynamical lattice gauge models

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We show how to simulate models with gauge symmetry in the lattice using atomic and quantum optics tools and tensor network methods. The construction is based on quantum links that realize continuous gauge symmetry with discrete quantum variables. At low energies, quantum link models with staggered fermions emerge from a Hubbard-type model that can be quantum simulated. These systems share qualitative features with quantum chromodynamics, including chiral symmetry breaking and restoration at non-zero temperature or baryon density.

In this presentation, we will construct a quantum simulator for an abelian gauge theory coupled to fermionic matter. This will allow us to investigate the phenomena of string breaking due to the creation of a pair particle-antiparticle as well as the real-time evolution after a quench in gauge theories [1] [2] [3] [4] [5] [6].

[1] Atomic quantum simulation of dynamical gauge fields coupled to fermionic matter : from string breaking to evolution after a quench, Phys. Rev. Lett. 109, 175302 (2012).

[2] Atomic quantum simulation of U(N) and SU(N) non-abelian lattice gauge theories, Phys. Rev. Lett. 110, 125303 (2013).

[3] Superconducting circuits for quantum simulation of dynamical gauge fields, Phys. Rev. Lett. 111, 110504 (2013).

[4] Tensor networks for Lattice Gauge Theories and Atomic Quantum Simulation, Phys. Rev. Lett. 112, 201601 (2014).

[5] Lattice Gauge Tensor Networks, arXiv :1404.7439 (2014)

[6] Two-dimensional Lattice Gauge Theories with Superconducting Quantum Circuits, arXiv :1407.6066 (2014)

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Suppression and Revival of Weak Localization through Manipulation of Time-Reversal Symmetry

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Coherent transport in disordered media has been a thriving topic for many decades. Started with the seminal paper by Anderson in 1958, introducing the possibility of strong localization of waves[1], the interest is still alive nowadays as open questions remain[2]. In the last years Anderson Localization was observed (in 1D[3] and 3D[4]) with ultra-cold atoms, allowing to study these phenomena in a precise way. Weak localization is manifested by the phenomenon of Coherent Backscattering (CBS)[5], i.e. the enhancement of the scattering probability in the backward direction. Time reversal symmetry is of central importance to constructive interferences of counter-propagating, multiple-scattering paths, giving rise to CBS.

Here we demonstrate the experimental breaking of the time reversal symmetry by applying a phase kick to the atoms during the propagation in the disorder as suggested by Micklitz *et al* [6]. We observe the suppression of weak localization as a disappearance of the CBS signal. At a specific propagation time the time reversal symmetry is restored and a short revival of the coherent signal is observed.

[1] P. W. Anderson, "Absence of Diffusion in Certain Random Lattices", *Phys. Rev.* **109**, 1492 (1958)
[2] A. Lagendijk, "Fifty years of Anderson localization", *Phys. Today*, **62**, 24 (2009)
[3] J. Billy et al. "Direct Observation of Anderson localization of matter-waves in a controlled disorder", *Nature* **453**, 891 (2008)
[4] F. Jendrzejewski et al. "'Three-dimensional localization of ultracold atoms in an optical disordered potential", *Nat. Phys.* **8**, 392 (2012)
[5] F. Jendrzejewski et al. "'Coherent Backscattering of Ultracold Atoms" , *Phys. Rev. Lett.* **109**, 195302 (2012)
[6] T. Micklitz et al. "'Echo spectroscopy of Anderson localization", *arXiv :*1406.6915 (2014)

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Hong-Ou-Mandel effect with matter waves

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We report on the direct observation of the coalescence of bosonic atoms, which is a paradigmatic effect of two-particle quantum interference. Our protocol closely follows the experiment of Hong, Ou and Mandel [1]. Pairs of atoms are emitted from a Bose-Einstein condensate in a four-wave mixing scattering process [2]. The atoms are subsequently deflected and overlapped on an atomic beam-splitter. By counting the number of atoms at each output ports with a time- and space-resolved detector, we quantify the tendency for the atoms to group in one port when they are indistinguishable.

[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).
[2] M. Bonneau, J. Ruaudel, R. Lopes, J.-C. Jaskula, A. Aspect, D. Boiron, and C. I. Westbrook,"Tunable source of correlated atom beams", Physical Review A **87**, 061603 (2013).

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Generation of squeezing and entanglement in external degrees of freedom with a BEC in double wells

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Production of non-classical and strongly correlated atomic states is an important step for the development of quantum atom optics. While lot of work has been done with spin states, we focus on external degrees of freedom, taking advantage of the tools available on atom chip traps.

Atom chips provide elongated trapping potentials for Bose-Einstein condensates (BEC), continuously tunable from single well to double wells.

In the double wells, we demonstrated coherent control of the relative population and phase between the two wells [1]. During the splitting process from single- to double wells, the atomic interactions produce a squeezing of the relative population. We present here our current work on splitting sequences improving this number-squeezing generation.

In the single well, we demonstrated coherent control of the BEC transverse motional state through shaking ramps defined by optimal control theory [2]. Transfer to the first excited transverse state was used to trigger twin-atom beams emission [3] : The only allowed decay mechanism to the transverse ground state involves scattering of two atoms, which transfers the transverse energy into longitudinal energy. Due to momentum conservation, the two atoms acquire opposite longitudinal momenta, and therefore are scattered into twin beams. These twin-atom beams are analogue to the twin-photon beams generated through parametric down-conversion, and widely used in quantum optics. Here, we present a scheme for production of entangled atom pairs through twin-atom beams emission in double wells : If twin-beam are produced in double wells, each atom pair will be emitted in a superposition of the two wells, of the form $|1L, 2L\rangle + e^{i\phi}|1R, 2R\rangle$, where L and R are the wells and 1 and 2 the atoms of the pair.

Characterization of the obtained non-classical atomic states is based on our unique light sheet fluorescence single-atom detector [4], perfectly suited for measurement of correlation functions.

[1] T. Berrada, S. van Frank, R. Bücker, T. Schumm, J.-F. Schaff, and J. Schmiedmayer, "Integrated Mach-Zehnder interferometer for Bose-Einstein condensates", Nat. Commun. **4**, 2077 (2013).

[2] S. van Frank, A. Negretti, T. Berrada, R. Bücker, S. Montangero, J.-F. Schaff, T. Schumm, T. Calarco, and J. Schmiedmayer, "Interferometry with non-classical motional states of a Bose-Einstein condensate", Nat. Commun. **5**, 4009 (2014).

[3] R. Bücker, J. Grond, S. Manz, T. Berrada, T. Betz, C. Koller, U. Hohenester, T. Schumm, A. Perrin and J. Schmiedmayer, "Twin-atom beams", Nat.Phys. **7**, 608 (2011). See also M. Bonneau, J. Ruaudel, R. Lopes, J.-C. Jaskula, A. Aspect, D. Boiron, and C. I.Westbrook, "Tunable source of correlated atom beams", Phys. Rev. A **87**, 061603 (2013) and poster by Denis Boiron.

[4] R. Bücker, A. Perrin, S. Manz, T. Betz, Ch. Koller, T. Plisson, J. Rottmann, T. Schumm, and J. Schmiedmayer, "Single-particle-sensitive imaging of freely propagating ultracold atoms", New J. Phys. **11**, 103039 (2009).

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A Dipolar Quantum Gas to simulate Quantum Magnetism

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I will present experimental results obtained in the Villetaneuse group with ultra cold chromium atoms. Due to the high spin (S=3) in the ground state of chromium, there are large magnetic dipole-dipole interactions between chromium atoms, which are long range, and anisotropic.

When we load our chromium BEC in a 3D lattice, we reach the correlated insulator Mott state, with one or two atoms per site. After atoms are prepared in the first excited Zeeman state (ms=-2), we study spin dynamics due to interactions at a distance. Our system is well described by an effective XXZ spin hamiltonian, with Ising and exchange terms.

The observed spin dynamics is in agreement with simulation including 9 spins on a 3*3 plaquette. This reveals the inherent many body character of the system [1]. We thus obtain an interesting system for quantum simulation, which realizes a spin model used in condensed matter physics with true spin-spin interactions.

As correlations build up between the few thousands of atoms loaded in the lattice, our system should reveal as well the existence of entanglement between many particles. A relevant experimental entanglement witness is currently searched in close collaboration with the group of Perola Milman at Paris 7.

[1] A. de Paz, A. Sharma, A. Chotia, E. Maréchal, J. H. Huckans, P. Pedri, L. Santos, O. Gorceix, L. Vernac, and B. Laburthe-Tolra, Phys. Rev. Lett. **111**, 185305 (2013)

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“Foundational aspects - FOUND”

1D-atoms applied to Fundamental Quantum Mechanics

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In the last few years, micro and nanofabrication of solid state systems have reached *quantum optical* level, i.e. it is now possible to manipulate the interaction of few photons and well defined discretized solid state emitters. These emitters can be quantum dots, defects or dopants in crystalline structures or collective motion of cooper pairs in superconductors. This has opened the possibility of building integrated circuits with effectively low dimensional matter systems able to respond to the smallest possible electromagnetic (E.M.) excitations such as single photons and channels that can transport these photons with very low losses. Atomic-like systems embedded in directional E.M. channels have been called 1-D atoms and are characterised by a modified spontaneous emission that is typically broadband in frequency but well defined in momentum. Such systems have been thoroughly studied in the last couple of years and in this work we explore some of its essential properties to discuss unorthodox aspects of the random nature of quantum systems.

Decoherence, present everywhere in the quantum world, is deeply connected to this intrinsic probabilistic nature of quantum physics. It is a mechanism considered to play a deleterious role in standard quantum applications but that since the development of quantum information theory has been explored as a positive feature for some protocols. For example, the same mechanism also allows for the secure quantum distribution of cryptographic keys or for the generation of propagating single photons on demand.

Spontaneous emission (s.e.) and optical (incoherent) pumping (i.p.) are two mechanisms usually associated to decoherence. A standard way of describing the dynamics of a bunch of individual emitters subjected to both s.e. and i.p. is to write down a non-unitary master equation for the overall density matrix of the system and a computationally efficient way to solve this equation is to unravel it into the convex sum of sequential dynamics of vectors, a method known as *Quantum Trajectories* (Q.T.). Designed as a numerical method to integrate the master equation, Q.T. has immediately gained an interesting physical interpretation connected to the changes in the dynamics of a given quantum system due to the constant recollection of information leaking from the system to its environment. However, even though the readout of the environment changes the dynamics of the system in each realization of a given experiment, it does not affect the random nature of the system-environment entanglement.

In this work, we show that albeit intrinsically random, the dynamics induced by processes such as s.e. and i.p. can be used not only to protect entanglement in quantum systems for very long times but also to efficiently and universally quantum compute in the system. Our result is based on the physical implementation of Q.T.s, i.e. it relies on the infinitely different possible ways to readout the information leaking to the environments. The whole computation is performed by optically pumping the individual emitters, something that happens at random times, waiting for them to release photons, another totally random process, and by detecting such photons in an adaptive way. It is also deterministically successful, i.e. in any given realization, the completely random sequence of events will still allow you to fully quantum compute any algorithm. Therefore, the fundamental conclusion one is able to draw is that random quantum evolutions are fuzzy if seen on average but can be quantum computationally efficient in any single realization of a given experiment. Or that nature is quantum computing all the time, but without adaptive intervention it ends up implementing random algorithms. Yet, another astonishing feature of the quantum world.

[1] A. R. R. Carvalho and M. F. Santos, New J. Phys. 13, 013010 (2011).
[2] M. F. Santos and A. R. R. Carvalho, EPL, 94, 64003 (2011)
[3] M. F. Santos, M. T. Cunha, R. Chaves and A. R. R. Carvalho, Phys. Rev. Lett., 108, 170501 (2012)

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Poster Contributions - Unsorted

Feshbach Insulator from Atom-Molecule Coherence of Bosons in Optical Lattices

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Feshbach resonances - namely resonances between an unbound two-body state (atomic state) and a bound (molecular) state, differing in magnetic moment - are a unique tool to tune the interaction properties of ultracold atoms [1]. Here we show that the spin-changing interactions, coherently coupling the atomic and molecular state [2–6], can lead to a novel insulating phase - the *Feshbach insulator* - for bosons in an optical lattice close to a *narrow* Feshbach resonance. Making use of quantum Monte Carlo simulations and mean-field theory, we show that the Feshbach insulator appears around the resonance, preventing the system from collapsing when the effective atomic scattering length becomes negative. On the atomic side of the resonance, the transition from condensate to Feshbach insulator has a characteristic *first-order* nature, due to the simultaneous loss of coherence in the atomic and molecular components. These features appear clearly in the ground-state phase diagram of *e.g.* ^{87}Rb around the 414 G resonance, and they are therefore directly amenable to experimental observation.

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[1] C. Chin, R. Grimm, P. Julienne, and E. Tiesinga, Rev. Mod. Phys. **82**, 1225 (2010).

[2] N. Syassen, D. M. Bauer, M. Lettner, D. Dietze, T. Volz, S. Dürr, and G. Rempe, Phys. Rev. Lett. **99**, 033201 (2007).

[3] M. W. J. Romans, R. A. Duine, S. Sachdev, and H. T. C. Stoof, Phys. Rev. Lett. **93**, 020405 (2004).

[4] K. Sengupta and N. Dupuis, Europhys. Lett. **70**, 586 (2005).

[5] S. Ejima, M. J. Bhaseen, M. Hohenadler, F. H. L. Essler, H. Fehske, and B. D. Simons, Phys. Rev. Lett. **106**, 015303 (2011).

[6] M. J. Bhaseen, S. Ejima, F. H. L. Essler, H. Fehske, M. Hohenadler, and B. D. Simons, Phys. Rev. A **85**, 033636 (2012).

Resonant dipole-dipole interactions in small systems of single Rydberg atoms

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Resonant energy transfers, the redistribution of an electronic excitation between two particles coupled by the dipole-dipole interaction, occur in a variety of chemical and biological phenomena [1], most notably photosynthesis. Here, we study, both spectroscopically and in the time domain, the coherent, dipolar induced exchange of electronic excitations between two single Rydberg atoms separated by a controlled distance, and brought in resonance by applying electric or microwave fields [2]. The coherent oscillation of the system between two degenerate pair states occurs at a frequency that scales as the inverse third power of the distance, the hallmark of dipole-dipole interactions [3]. We finally study the propagation of an excitation in a three-atom system, thus simulating the dynamics of an elementary spin-chain. These results show our ability to actively tune strong, coherent interactions, a useful tool for the quantum simulation of many-body systems.

[1] D. L. Andrews, and A. A. Demidov, "Resonance energy transfer", Wiley, (1999).
[2] S. Ravets, *et al.* "Coherent dipole-dipole coupling between two single atoms at a Förster resonance", arXiv :1405.7804 (2014).
[3] T. G. Walker, and M. Saffman, "Zeros of Rydberg-Rydberg Förster interactions", J. Phys. B : At. Mol. Opt. Phys. **38**, S309-S319 (2005).

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Step-by-step coherent population trapping with coupled single spins in diamond.

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Nuclear spins are attractive candidates for solid-state quantum information storage and processing owing to their extremely long coherence time [1]. However, since this appealing property results from a high level of isolation from the magnetic environment, it remains a challenging task to polarize, manipulate and readout individual nuclear spins [2].

In this work, we show room temperature coherent population trapping (CPT) with nuclear spins in diamond using single nitrogen-vacancy defect (Fig. 1-(a)). Thanks to this highly controlable system, we are able to investigate a stroboscopic regime of CPT experiment where coherent driving of the three-level system is decoupled from spontaneous emission relaxation. In this regime, we demonstrate that the dark state of the lambda system is obtained for multiple values of the two-photon detuning. We investigate in real time the building of the dark state (Fig. 1-(b)) and its robustness under decoherence induced by optical illumination.

This mechanism, which operates in the microwave domain, could find applications in solid-state quantum information, micro-wave photon storage and hybrid system spin-superconducting resonator.

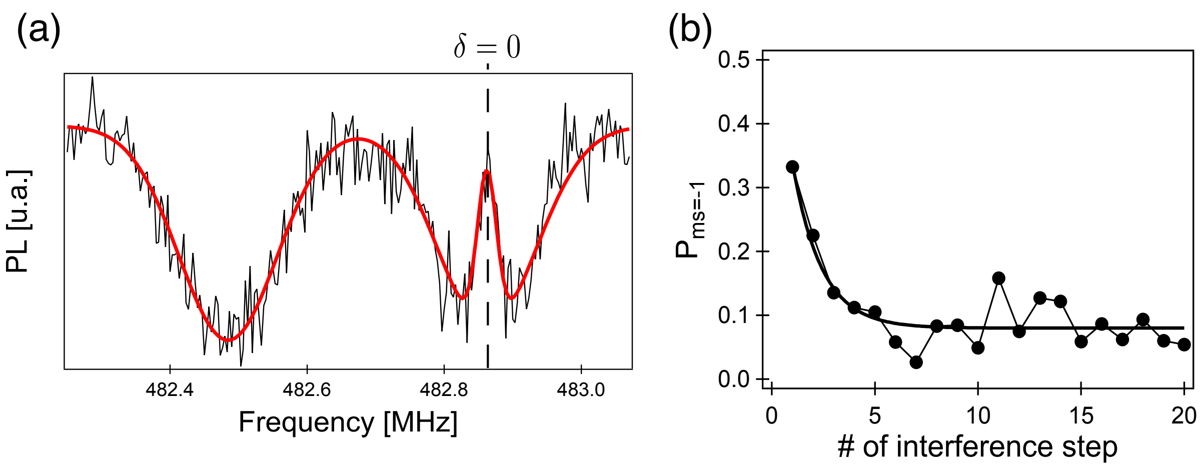

FIGURE 1. (a) Electron spin resonance experiment on a single NV defect coupled to a ^{13}C nuclear spin. Coherent population trapping is manifest in the change of the excited state probability close to the two-photon resonance ($\delta = 0$). (b) Excited state population of the spin lambda system at the two-photon resonance as function of the number of CPT pumping steps.

[1] T. D. Ladd, *et al.*, Nature (London) **464**, 45 (2010).
[2] E. Togan, *et al.*, Nature **478**, 497-501 (2011) .

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On-demand maximally entangled states with a parity meter and continuous feedback

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The basic idea that parity measurements could be used to create entanglement is theoretically established by more than 10 years. Moreover, parity measurements can be realized in different solid state implementations, e.g. for superconducting qubits in resonant superconducting cavities [1, 2], and for quantum dots coupled to an electronic Mach-Zehnder interferometer [3] or to a quantum point contact [4]. A major problem in all these implementations is that the unavoidable back-action of the measurement hinder the realization of certain maximally entangled states. Importantly, such a decoherence has been recently reported in experiments with superconducting qubits in the groups of Dicarlo in Delft and Siddiqi in Berkeley [5–7].

Our work puts forward a scheme to overcome this dangerous decoherence effect : in fact we propose to use different quantum feedback protocols to stabilize the steady state of the system to any maximally entangled states defined a priori [8]. While quantum feedback protocols are well established theoretically, and have recently been realized experimentally for single qubits [9], their application to parity measurement presents substantial differences with respect to the single qubit case.

We analyze the parity measurement of two double quantum dots serving as qubits via an electronic MZI. We present a microscopic derivation of the detector outcome and its back-action, which allows us to study numerically different feedback schemes. We show that a direct feedback based on parity measurement only allows to overcome the measurement-induced dephasing within each parity subspace, leading to a larger and longer-lasting entanglement. While this scheme is inefficient for external noise sources (e.g. gate voltage fluctuations), we show that a more elaborate scheme requiring two simultaneous measurements and a single feedback channel leads to a steady state entanglement, whose amount depends on the feedback efficiency.

By combining continuous feedback with parity measurements, our results provide a further step towards the key goal of entanglement generation and qubits stabilization for quantum information processing.

[1] K. Lalumière, J. M. Gambetta, and A. Blais, "Tunable joint measurements in the dispersive regime of cavity QED", Phys. Rev. A **81**, 040301 (2010).
[2] L. Tornberg, and G. Johansson, "High-fidelity feedback-assisted parity measurement in circuit QED", Phys. Rev. A **82**, 012329 (2010).
[3] G. Haack, H. Förster, and M. Büttiker, "Parity detection and entanglement with a Mach-Zehnder interferometer", Phys. Rev. B **82**, 155303 (2010).
[4] B. Trauzettel, A. N. Jordan, C. W. J. Beenakker, and M. Büttiker, "Parity meter for charge qubits : An efficient quantum entangler", Phys. Rev. B **73**, 235331 (2006).
[5] D. Ristè *et al.*, "Deterministic entanglement of superconducting qubits by parity measurement and feedback", Nature (London) **502**, 350 (2013).
[6] N. Roch *et al.*, "Observation of Measurement-Induced Entanglement and Quantum Trajectories of Remote Superconducting Qubits", Phys. Rev. Lett. **112**, 170501 (2014).
[7] O.-P. Saira *et al.*, "Entanglement Genesis by Ancilla-Based Parity Measurement in 2D Circuit QED", Phys. Rev. Lett. **112**, 070502 (2014).
[8] C. Meyer zu Rheda, G. Haack, A. Romito, "On-demand generation of steady maximally-entangled states via a parity measurement with feedback", arXiv :1407.1159 (2014).
[9] R. Vijay *et al.*, "Stabilizing Rabi oscillations in a superconducting qubit using quantum feedback", Nature **490**, 77 (2012).

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Decay of Bogoliubov quasiparticles in a nonideal one-dimensional Bose gas

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Excitation spectrum in weakly-interacting systems of bosons have the Bogoliubov form. In three dimensions, those excitations are unstable due to residual weak interactions. The resulting process is known as Beliaev decay [1, 2] and has been experimentally observed [3]. The related problem of decay of excitations in one-dimensional Bose gases is a fundamental long-standing problem. In this talk I will present its solution [4]. As a result of the conservation laws in one dimension, at zero temperature the leading mechanism for decay of a quasiparticle excitation is its disintegration into three others. We find that a phonon excitation has a decay rate proportional to the seventh power of momentum. In the integrable case of contact interaction between the bosons, the decay rate vanishes. Our theory is based on studying the anharmonic effects produced by the leading integrability breaking perturbations to the Lieb-Liniger model.

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[1] S. T. Beliaev, Sov. Phys. JETP **7**, 299 (1958).

[2] L. D. Landau and E. M. Lifshitz, Statistical Physics, Part 2 (Pergamon Press, Oxford, 1980).

[3] N. Katz, J. Steinhauer, R. Ozeri, and N. Davidson, Phys. Rev. Lett. **89**, 220401 (2002).

[4] Z. Ristivojevic and K. A. Matveev, Phys. Rev. B **89**, 180507(R) (2014).

Laguerre-Gaussian laser modes for atomic physics : cold atom channeling and information storage

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Laguerre-Gaussian laser modes are ring of light having a helical phase. The phase structure is known to be responsible of an orbital angular momentum (OAM) of light. This quantity is quantified by an integer ℓ and the Laguerre-Gaussian mode basis constitutes a way to encode the information. The two properties -annular intensity and helical phase- are used in the context of atomic physics either to manipulate the atoms or to store quantum information in an atomic ensemble. We will present the Laguerre-Gaussian laser modes, theirs properties and the methods to generate them. Then two examples will be given in atomic physics :

(1) Long-distance channeling of cold atoms exiting a 2D magneto-optical trap by a Laguerre-Gaussian laser beam [1]. In this experiment done in Orsay, by using a blue-detuned laser, shaped into a Laguerre-Gaussian (LG) mode we channel atoms exiting a 2-dimensional magneto-optical trap (2D-MOT) over a 30 cm distance. Compared to a freely propagating beam, the atomic flux (about 10^{10}at/s) is conserved whereas the divergence is reduced from 40 to 3 milli-radians. So, 30 cm far the 2D-MOT exit, the atomic beam has a 1 mm diameter and the atomic density is increased by a factor of 200. Such a LG-channeled-2D-MOT with a high density flux is a promising device for many applications as loading a 3D-MOT. The device has been studied versus the order of the LG mode (from 2 to 10) and versus the laser-atom frequency detuning (from 2 to 120 GHz). A clever version in which the LG mode frequency is locked to the repumping transition allows us to run the setup with two lasers instead of three.

(2) Storage and Non-Collinear Retrieval of Orbital Angular Momentum of Light in Cold Atoms [2]. Using a nonlinear interaction of OAM beams with an atomic vapour via four-wave mixing (FWM) processes it has been demonstrated that OAM can be stored and retrieved, allowing atomic memories. Differently from the previous observations, we demonstrated that the stored OAM beam is retrieved along a non-collinear direction.The experiment in collaboration with Tabosa's group (Recife) is performed in cold Cs atoms from a MOT, using a delayed FWM configuration with a writing beam W carrying a topological charges $\ell = 0, 1, 2, 3$. The phase structure of is stored into the Zeeman coherence grating induced by the incident writing beams and is restored when a reading beam is switched on. The retrieved beam, monitored by a CCD camera, shows the transfer and conservation of OAM.

[1] V. Carrat, C. Cabrera-Gutiérrez, M. Jacquey, J. W. Tabosa, B. Viaris de Lesegno, and L. Pruvost, "Long-distance channeling of cold atoms exiting a 2D magneto-optical trap by a Laguerre-Gaussian laser beam", Opt. Lett. **39**, 719-722 (2014).
[2] R. A. de Oliveira, L. Pruvost, P. S. Barbosa, W. S. Martins, S. Barreiro, D. Felinto, D. Bloch, and J. W. R. Tabosa, "Off-axis retrieval of orbital angular momentum of light stored in cold atoms", submitted.

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Achieving single-shoton nonlinearities with an intracavity Rydberg medium

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

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

Here, our atomic cloud is placed into a one-ended low finesse optical cavity which amplifies the nonlinear effects[8]. We are also able to perform second-order correlation measurements and homodyne detections of the outgoing field[9].

We will present our current efforts to observe nonlinear effects at the single-photon level. This includes the implementation of a dipole trap to increase the atomic density, or increasing the cavity finesse and its concentricity. We aim at observing bunching or anti-bunching of light and phase jumps induced by Rybderg excitations in our intracavity cloud.

[1] J. D. Pritchard *et al.*, *Annu Rev of Cold Atoms and Molecules* 301-350 (2013).
[2] M. D. Lukin *et al.*, *Phys. Rev. Lett.* **87** 037901 (2001).
[3] T. Peyronel *et al.*, *Nature* **488** 57 (2012).
[4] Y. O. Dudin *et al.*, *Science* **336** 887 (2012).
[5] O. Firstenberg *et al.*, *Nature* **502** 71 (2013).
[6] D. Tiarks *et al.*, *Phys. Rev. Lett.* **113** 053602 (2014).
[7] H. Gorniaczyk *et al.*, *Phys. Rev. Lett.* **113** 053601 (2014).
[8] V. Parigi *et al.*, *Phys. Rev. Lett.* **109** 233602 (2012).
[9] E. Bimbard *et al.*, *Phys. Rev. Lett.* **112** 033601 (2014).

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Generating entanglement via measurement between two remote superconducting qubits

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Measurement has traditionally been viewed as a mechanism for restoring classical behavior : a quantum superposition, once observed, transforms into a single classical state. However, for some quantum systems it is possible to design a measurement that probabilistically projects onto an entangled state, thereby purifying, rather than destroying, quantum correlations. We use a joint dispersive readout to entangle two superconducting qubits, in individual cavities, separated by more than a meter of coaxial cable. We obtain a concurrence of 0.35, which is consistent with transmission losses and detector efficiency. The intensity of the readout pulse can be continuously varied, enabling us to monitor the dynamics of entanglement generation. The data agree with both a Bayesian model and a full master equation treatment.

[1] Roch, N. and Schwartz, M. E. and Motzoi, F. and Macklin, C. and Vijay, R. and Eddins, A. W. and Korotkov, A. N. and Whaley, K. B. and Sarovar, M. and Siddiqi, I., "Generating entanglement via measurement between two remote superconducting qubits", Phys. Rev. Lett. **112**, 170501 (2014).

An integrated source of filtered photon pairs for large scale quantum photonic systems

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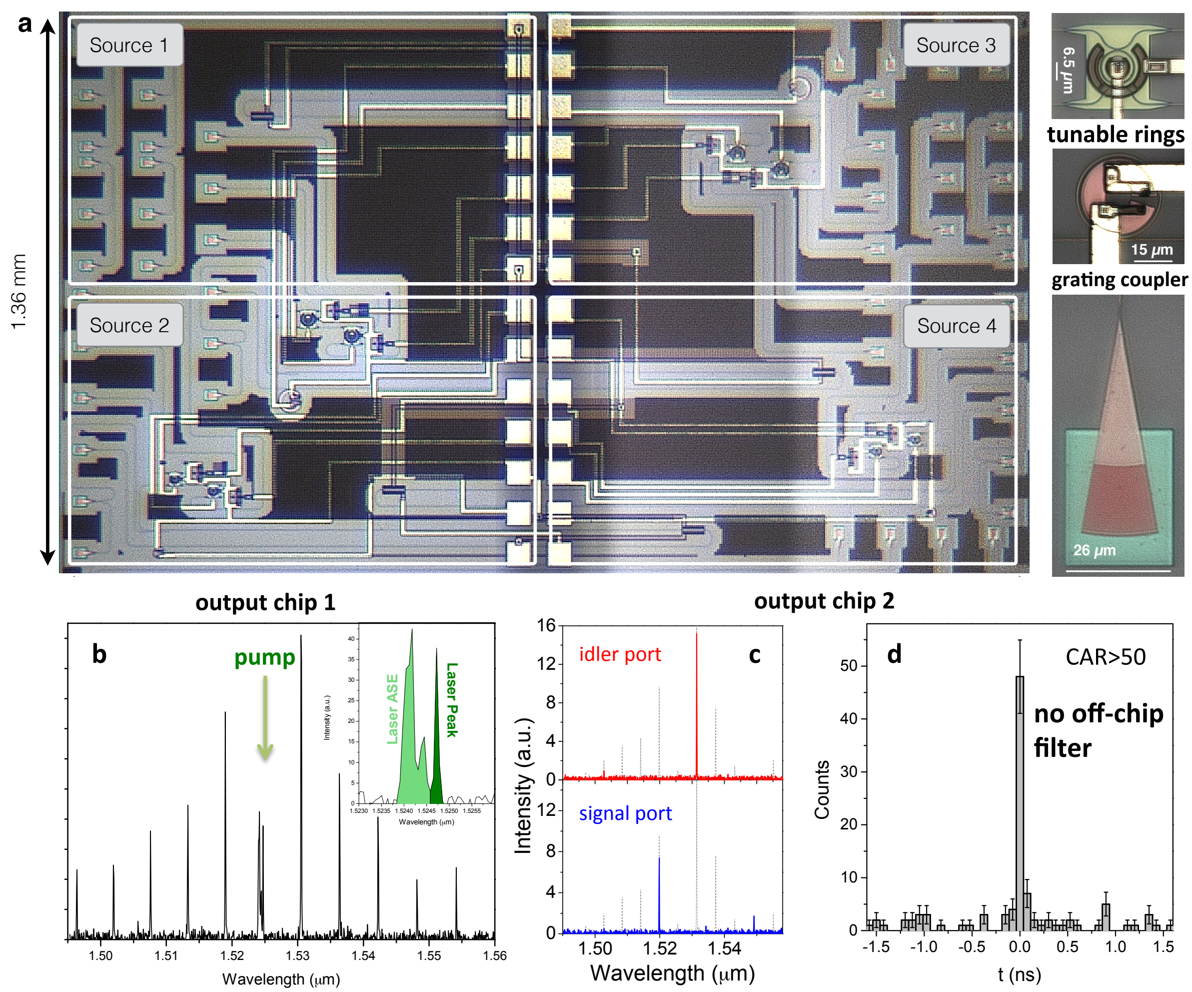
We demonstrate the first on-chip (Fig. **a**) spectral filtering of quantum-correlated photons generated by spontaneous four-wave mixing in a silicon ring resonator. Pump rejection by more than 95 dB in a single chip (Fig. **b**) and demultiplexing of signal and idler photons transfered via a fiber to another identical chip (Fig. **c**) are achieved with reconfigurable silicon photonic integrated circuits based on Bragg reflectors and tunable ring resonators. Non-classical two-photon temporal correlations are measured at the output of the second chip without further off-chip filtering (Fig. **d**). Our system, fabricated with high yield and reproducibilty, paves the way toward truly large scale quantum photonic circuits by allowing photon sources and detectors to be integrated on the same chip.



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Correlation cone and supersonic correlations in one- and two-dimensional bosonic superfluids

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The dynamics of correlated quantum systems is attracting a growing attention, sparked by the recent development of quantum devices with long coherence times and dynamical control of parameters, e.g. superconducting circuits and ultracold atoms. These systems now allow us to address basic questions that would have been considered purely academic only a few years ago. For instance, how does information spread in a correlated quantum system ? How does an isolated quantum system prepared out of equilibrium relaxes to a state well described by equilibrium thermodynamics ? What is the dynamics of thermalization processes ? The recent years have witnessed landmark progress towards understanding those basic phenomena, both theoretical [1, 2] and experimental [3–5].

In this contribution I will present recent results on the out-of-equilibrium dynamics of interacting lattice bosons [6]. In particular, we study how (and how fast) correlations spread in a quantum system abruptly driven out of equilibrium by a quantum quench. We focus on the spreading of density-density correlations in Bose-Hubbard models after a quench of the interaction strength, using time-dependent variational Monte Carlo simulations [7]. This method gives access to unprecedented long propagation times and to dimensions higher than one. In both one and two dimensions, we demonstrate the existence of a "correlation-cone", characterized by the ballistic spreading of correlations with a finite propagation time. We extract accurate values of the correlation-cone velocity in the superfluid regime and show that the spreading of correlations is generally supersonic. Further, we show that in two dimensions the correlation spreading is highly anisotropic and presents nontrivial interference effects.

[1] S. Bravyi, M.B. Hastings, and F. Verstraete, Phys. Rev. Lett. 97, 050401 (2006).
[2] P. Calabrese and J. Cardy, Phys. Rev. Lett. 96, 136801 (2006).
[3] M. Cheneau *et al.*, Nature **481**, 484 (2012).
[4] S. Trotzky, Y.-A. Chen, A. Flesch, I.P. McCulloch, U. Schollwöck, J. Eisert, and I. Bloch, Nat. Phys. 8, 325 (2012).
[5] T. Langen *et al.*, Nat. Phys. **9**, 640 (2013).
[6] G. Carleo, F. Becca, L. Sanchez-Palencia, S. Sorella, and M. Fabrizio, Phys. Rev. A **89**, 031602(R) (2014).
[7] G. Carleo, F. Becca, M. Schiro, and M. Fabrizio, Sci. Rep. 2, **243** (2012).

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Discrete Lorentz covariance for Quantum Walks and Quantum Cellular Automata

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For the purpose of quantum simulation (on a quantum device) as envisioned by Feynman [1], or for the purpose of exploring the power and limits of discrete models of physics, a great deal of effort has gone into discretizing quantum physical phenomena. Most of these lead to Quantum Walk (QW) models of the phenomena. QWs are dynamics having the following features :

– The underlying spacetime is a discrete grid ;
– The evolution is unitary ;
– It is causal, i.e. information propagates strictly at a bounded speed.
– It is homogeneous, i.e. translation-invariant and time-independent.

By definition, therefore, they have several of the fundamental symmetries of physics, built-in. But can they also have Lorentz covariance ? In this contribution [2] we formalize a notion of discrete Lorentz transforms for Quantum Walks (QW) and Quantum Cellular Automata (QCA), in $(1+1)$-dimensional discrete spacetime. The theory admits a diagrammatic representation in terms of a few local, circuit equivalence rules. Within this framework, we show the first-order-only covariance of the Dirac QW. We then introduce the Clock QW and the Clock QCA, and prove that they are exactly discrete Lorentz covariant. The theory also allows for non-homogeneous Lorentz transforms, between non-inertial frames.

[1] Feynman, R. P., "Simulating physics with computers", International Journal of Theoretical Physics **21**, 6, 467-488 (1982).
[2] Arrighi, Pablo and Facchini, Stefano and Forets, Marcelo, "Discrete Lorentz covariance for Quantum Walks and Quantum Cellular Automata", New J. Phys. 16 (2014) 093007.

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Coherent backscattering in the Fock space of a disordered Bose-Hubbard system

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We predict a generic signature of quantum interference in many-body bosonic systems resulting in a coherent enhancement of the average return probability in Fock space [1]. This enhancement is robust with respect to variations of external parameters even though it represents a dynamical manifestation of the delicate superposition principle in Fock space. It is a genuine quantum many-body effect which lies beyond the reach of any mean-field approach. Using a semiclassical approach based on interfering paths in Fock space, we calculate the magnitude of the backscattering peak and its dependence on gauge fields that break time-reversal invariance. We confirm our predictions by comparing them to exact quantum evolution probabilities in Bose-Hubbard models, and discuss their relevance in the context of manybody thermalization. We furthermore propose a specific experimental setup in order to detect this many-body coherent backscattering phenomenon with ultracold bosonic atoms

[1] T. Engl, J. Dujardin, A. Argüelles, P. Schlagheck, K. Richter, and J. D. Urbina, "Coherent Backscattering in Fock Space : a Signature of Quantum Many-Body Interference in Interacting Bosonic Systems", Phys. Rev. Lett. **112**, 140403 (2014).

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Node for microwave quantum network

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We have recently realized a superconducting device able to both catch, store and release a quantum microwave signal on demand, and to generate entanglement between the device and a propagating mode of a transmission line. Specifically, a dynamically tunable coupling is implemented between two resonators by a nonlinear superconducting circuit based on a ring of four Josephson junctions. In the first experiment on this device, the higher quality factor resonator, also referred to as memory, was able to store a signal for a few microseconds and release it on-demand in about 100 ns. I will show how we plan to improve the figures of merit of the memory with quantum information protocols in mind, such as remote state preparation and teleportation of a microwave quantum state. These protocols can be readily demonstrated using the entanglement between the memory and the propagating mode if we use a superconducting qubit as a way to prepare and measure exotic cavity states.

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Steady many-body entanglement induced by an out of thermal equilibrium environment

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This work concerns the manipulation of quantum systems by engineering the properties of the environment they interact with. It is based on recent studies regarding the properties of the radiation field produced in a given configuration when macroscopic bodies are kept at different temperatures [1]. Indeed, it has been shown that the interaction of small atomic systems (one or two atoms) with a field produced in a configuration kept out of thermal equilibrium may permit a strong manipulation of the atomic dynamics [2–4].

Here we study an ensemble of more than two two-level quantum systems (qubits) interacting with a common electromagnetic field in proximity of a dielectric slab whose temperature is held different from that of some far surrounding walls (see Fig. 1). We show that the dissipative dynamics of the qubits driven by this stationary and out of thermal equilibrium (OTE) field, allows the production of steady many-body entangled states, differently from the case at thermal equilibrium where steady states are always non-entangled. By studying up to ten qubits, we point out the role of symmetry in the entanglement production, which is exalted in the case of permutationally invariant configurations. In the case of three qubits, we find a strong dependence of tripartite entanglement on the spatial disposition of the qubits, and in the case of six qubits, we find several highly entangled bipartitions where entanglement can, remarkably, survive for large qubit-qubit distances up to 100 μm [5].

Our analysis points out the potentialities of rich yet simple configurations involving macroscopic bodies held at different temperature, which are within experimental reach. They may permit the production and manipulation of steady multipartite entanglement, resistant for large inter-qubits distances, offering then new tools possibly exploitable for quantum computational tasks. All this is obtained without any further external actions on the qubits, being the result of the qubits dissipative dynamics itself. These protocols are then intrinsically robust to environmental effects and do not need of initializing the total system in a given configuration.

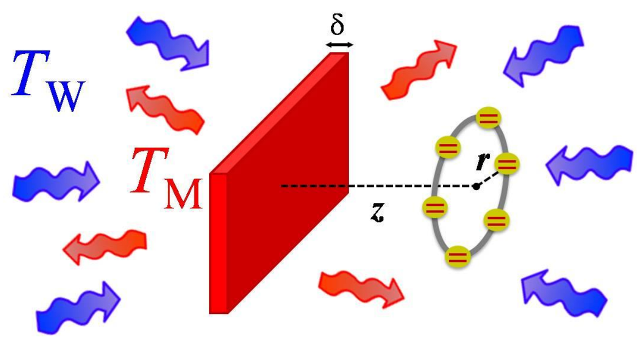

FIGURE 1. Several qubits close to a slab at temperature T_{M} different from the temperature of some far surrounding walls, T_{W}.

[1] R. Messina and M. Antezza, Phys. Rev. A **84**, 042102 (2011) ; Europhys. Lett. **95**, 61002 (2011).
[2] B. Bellomo, R. Messina, and M. Antezza, Europhys. Lett. **100**, 20006 (2012).
[3] B. Bellomo, R. Messina, D. Felbacq, and M. Antezza, Phys. Rev. A **87**, 012101 (2013).
[4] B. Bellomo and M. Antezza, Europhys. Lett. **104**, 10006 (2013) ; New J. Phys. **15**, 113052 (2013).
[5] B. Bellomo and M. Antezza, arXiv :1409.7178.

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Multiqubit symmetric states with maximally mixed one-qubit reductions

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We present a comprehensive study on the remarquable properties shared by maximally entangled symmetric states of arbitrary numbers of qubits in the sense of the maximal mixedness of the one-qubit reduced density operator. Such states are of great interest in quantum information as they maximize several measures of entanglement, such as Meyer-Wallach entropy [1] and any entanglement monotone based on linear homogenous positive functions of pure state within their SLOCC classes of states [2, 3]. When they exist, they are unique up to local unitaries within their SLOCC classes [3, 4]. They play a specific role in the determination of the local unitary equivalence of multiqubit states [5]. Moreover, they are maximally fragile (in the sense that they are the states which are the most sensitive to noise) and have therefore been proposed as ideal candidates for ultrasensitive sensors [6]. They appear in the litterature under various names : maximally entangled states [6], 1-uniform states [7], normal forms [3, 4] and nongeneric states [5].

We present a general criterion to easily identify whether given symmetric states are maximally entangled or not [9]. We show that these maximally entangled symmetric (MES) states are the only symmetric states for which the expectation value of the associated collective spin $\hat{\mathbf{S}}$ of the system vanishes, which coincides with the definition of anticoherence to order one of spin states. This definition also coincides with the cancellation of the dipole moment of the Husimi function of the state. We then generalize these properties and show that a state is anticoherent to order t, namely $\langle(\hat{\mathbf{S}}\cdot\mathbf{n})^k\rangle$ is independent of $\mathbf{n}$ for $k = 1, \ldots, t$, where $\mathbf{n}$ is a unit vector, iff it has maximally mixed t-qubit reductions or iff all moments up to order 2^t of its Husimi function vanish. We also establish the equivalence between anticoherent states to order t and unpolarized light states to order t [8], thereby encompassing various state characterizations under the same banner [9, 10].

We provide a nonexistence criterion allowing us to know immediately whether SLOCC classes of symmetric states can contain MES states or not. We show in particular that the symmetric Dicke state SLOCC classes never contain such MES states, with the only exception of the balanced Dicke state class for even numbers of qubits. We analyze the 4-qubit system exhaustively and identify and characterize all MES states of this system as well as the only 4-qubit state anticoherent to order 2. Finally, we analyze the entanglement content of MES states with respect to the geometric [11] and barycentric [12] measures of entanglement.

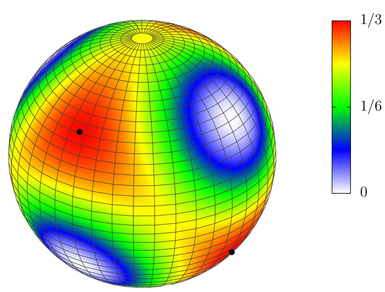

Figure1. Density plot of the Husimi function associated with the only 4-qubit symmetric state anticoherent to order 2.

[1] D. A. Meyer and N. R. Wallach, J. Math. Phys. **43**, 4273 (2002).
[2] Classes of states equivalent through stochastic local operations with classical communication.
[3] F. Verstraete, J. Dehaene, and B. De Moor, Phys. Rev. A **68**, 012103 (2003).
[4] G. Gour and N. Wallach, N. J. Phys. **13**, 073013 (2011).
[5] B. Kraus, Phys. Rev. Lett. **104**, 020504 (2010).
[6] N. Gisin and H. Bechmann-Pasquinucci, Phys. Lett. A **246**, 1 (1998).
[7] A. J. Scott, Phys. Rev. A **69**, 052330 (2004).
[8] L. L. Sánchez-Soto, A. B. Klimov, P. de la Hoz, and G. Leuchs, J. Phys. B : At. Mol. Opt. Phys. **46**, 104011 (2013).
[9] D. Baguette, T. Bastin, and J. Martin, Phys. Rev. A **90**, 032314 (2014).
[10] O. Giraud, D. Braun, D. Baguette, T. Bastin, and J. Martin, arXiv :1409.1106.
[11] T.-C. Wei and P. M. Goldbart, Phys. Rev. A **68**, 042307 (2003).
[12] W. Ganczarek, M. Kuś, and K. Życzkowski, Phys. Rev. A **85**, 032314 (2012).

Experimental heralded amplification of time-bin qubits

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Quantum Communication (QC) protocols are based on qubits encoded on photons at telecommunication wavelengths, due to the high transmission efficiency in single mode optical fibres. However, above a certain distance, losses start to become significant also for telecom light, requiring amplification stages before detection. Deterministic amplification of quantum states is generally not possible due to the no-cloning theorem, but it is achievable in a probabilistic scheme thanks to Heralded Noiseless Amplification of photons[1]. In particular, protocols based on Device Independent Quantum Key Distribution (DI-QKD) require a means to overcome transmission losses of quantum channels, in order to observe the violation of a Bell inequality free from the detection loophole. This task has been shown to be well performed by heralded qubit amplifiers[2].

The principle of heralded qubit-amplification can be summarized as follows. When a heralded single photon is prepared in a time-bin qubit of the form $|\psi\rangle = |H,\ell\rangle + e^{i\phi}|V,s\rangle$ (where $H,\ell/V,s$ means horizontal, long/vertical, short) and then sent through a channel with transmission p, it will change its state into $\rho_{in} = (1-p)|0\rangle\langle 0| + p|\psi\rangle\langle\psi|$. A pair of ancillary photons in the state $|H,\ell\rangle|V,s\rangle$ is needed to perform the amplification. In order to achieve succesfull and coherent amplification, the three photons involved in the process must be indistinguishable. The qubit amplification consists of a teleportation with a gain $g(t)$, leading to an output state of the form $\rho_{out} = 1/N(t)\left[(1-p)|0\rangle\langle 0| + g(t)^2 p|\psi\rangle\langle\psi|\right]$. The two polarisation modes allow one to separate the ℓ and s components in the time-bin analyser without losses .

Heralded amplification of telecom photons has been experimentally realized in completely fibre-based systems [3] or in a bulk setup exploiting polarisation modes [4], and proved to be a coherent process with good performances with respect to typical network transmission efficiencies. Amplification of polarisation qubits has been successfully demonstrated by doubling a single photon amplifier stage for the two orthogonal polarisations [5]. Here we present the realisation and characterisation of a heralded amplifier of time-bin qubits, optimised to compensate transmission losses of a typical network distance ($\sim$ 20km). The setup is low-loss fibre based, allowing one to build a plug and play device with a fixed gain suitable for DI-QKD protocols and other quantum communication technologies. In addition, the photons used in our setup are created in a separable state with high heralding efficiency[6]. This allows one to avoid filtering losses, making the source optimal for QC and proof of principle tests, where high interference visibility between independent sources is often needed together with low-loss configurations.

[1] T. C. Ralph and A. P. Lund, "Nondeterministic Noiseless Linear Amplification of Quantum Systems" in Proceedings of the 9th Interna- tional Conference on Quantum Communication, Measurement and Computing, edited by A. Lvovsky (AIP, New York, 2009), pp. 155-160.
[2] N. Gisin, S. Pironio, and N. Sangouard, "Proposal for Implementing Device-Independent Quantum Key Distribution Based on a Heralded Qubit Amplifier", Phys. Rev. Lett. **105**, 070501 (2010).
[3] C. I. Osorio, N. Bruno, N. Sangouard, H. Zbinden, N. Gisin, and R. T. Thew, "Heralded photon amplification for quantum communication", Phys. Rev. A **86**, 023815 (2012)
[4] N Bruno, V Pini, A Martin, R T Thew, "A complete characterization of the heralded noiseless amplification of photons", New J. Phys. **15**, 093002 (2013)
[5] S. Kocsis, G. Y. Xiang, T. C. Ralph and G. J. Pryde, "Heralded noiseless amplification of a photon polarization qubit", Nat. Phys. **9**, 2328 (2013)
[6] N. Bruno, A. Martin, T. Guerreiro, B. Sanguinetti, and R. T. Thew , "Pulsed source of spectrally uncorrelated and indistinguishable photons at telecom wavelengths", Opt. Exp. **22**, 14 (2014)

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Witnessing single photon entanglement with weak displacement detection

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Quantum nonlocality is usually attributed to correlations between two or more spatially separated particles. However, it was shown in [1] that the same correlations are also present in the state $1/\sqrt{2}[|1\rangle_A|0\rangle_B + |0\rangle_A|1\rangle_B]$, in the Fock representation, where A and B indicates two modes respectively. It was also proposed that this effect could be measured by phase sensitive measurements, later experimentally validated by [2, 3].

Here we propose another way of probing these correlations, based on single photon detector placed after a small displacement operation (that is performed with a local oscillator). This configuration can be used to measure the state in the X and Z basis by turning the coherent state on and off respectively. We use this detection scheme to violate a novel entanglement witness. Our setup can also produce and probe states like $a|1\rangle_A|0\rangle_B + b|0\rangle_A|1\rangle_B$, ranging from maximally entangled to separable states, showing a clear violation of the witness even for values of a^2 as low as 0.1, indicating the robustness of our approach. Moreover, this approach can be extended to a multipartite scenario.

[1] S. M. Tan, Physical Review letters **66**, 252 (1991).
[2] B. Hessmo, Physical Review letters **92**, 180401 (2004).
[3] Melvyn Ho, arXiv :1406.0381v1.

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Multibody Interacting Bosons

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Effective multibody interactions can arise even in a purely two-body interacting system when one integrates out some of its (high energy) degrees of freedom or substitutes the actual two-body potential by a pseudopotential. Such effective forces are important in many fields from nuclear and high-energy physics to ultracold gases. In recent years various possibilities to independently control multibody interactions have been discussed and a number of more or less technically complicated schemes has been suggested. The task is not straightforward but highly rewarding because of many potentially interesting implications, in particular, for the creation of topological quantum Hall phases, stabilizing paired bosonic superfluids, observing self-trapped droplets and other phenomena.

Here we propose a method of controlling two- and three-body interactions in an ultracold Bose gas in any dimension. The method requires to have two coupled internal single-particle states split in energy such that the upper state is occupied virtually but amply during collisions. By varying system parameters one can switch off the two-body interaction while maintaining a strong three-body one. The mechanism can be implemented for dipolar bosons in the bilayer configuration with tunnelling or in an atomic system by using radio-frequency fields to couple two hyperfine states [1]. We also consider the problem in an optical lattice and show that by coupling two hyperfine states of an atom one can independently control two-, three-, and four-body on-site interactions in a nonperturbative manner [2]. In particular, under typical conditions of current experiments one can have a purely three- or four-body interacting gas of ^{39}K atoms characterized by on-site interaction shifts of several 100Hz.

[1] D.S. Petrov, "Three-Body Interacting Bosons in Free Space", Phys. Rev. Lett. **112**, 103201 (2014).
[2] D.S. Petrov, "Elastic Multibody Interactions on a Lattice", Phys. Rev. A **90**, 021601(R) (2014).

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Vortex and Meissner phases of strongly-interacting bosons on a two-leg ladder

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We establish the phase diagram of the strongly-interacting Bose-Hubbard model defined on a two-leg ladder geometry in the presence of a homogeneous flux. Our work is motivated by a recent experiment [1], which studied the same system, in the complementary regime of weak interactions. Based on extensive density matrix renormalization group simulations and a bosonization analysis, we fully explore the parameter space spanned by filling, inter-leg tunneling, and flux. As a main result, we demonstrate the existence of gapless and gapped Meissner and vortex phases, with the gapped states emerging in Mott-insulating regimes [2]. We calculate experimentally accessible observables such as chiral currents and vortex patterns.

[1] M. Atala, M. Aidelsburger, M. Lohse, J. T. Barreiro, B. Paredes and I. Bloch, "Observation of chiral currents with ultracold atoms in bosonic ladders", Nat. Phys. **10**, 588 (2014).

[2] M. Piraud, F. Heidrich-Meisner, I. P. McCulloch, S. Greschner, T. Vekua and U. Schollwöck, "Vortex and Meissner phases of strongly-interacting bosons on a two-leg ladder", arXiv :1409.7016 (2014).

Remote creation of optical hybrid entanglement between discrete and continuous variables

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The development of optical quantum information processing has followed two complementary approaches : the discrete- and the continuous-variable ones, each exploiting either particle or wave nature of light [1]. The first one involves single-photons, while the continuous alternative encodes information in quadrature components of a light field, for instance using arbitrary superpositions of classical light waves with opposite phases, $c_0|\alpha\rangle + c_1|-\alpha\rangle$. In recent years, there has been a significant progress in combining both approaches with a view to realizing hybrid protocols that overcome the current limitations. In this endeavor, hybrid entanglement between particle-like and wave-like qubits, i.e. of the form $|0\rangle|\alpha\rangle + |1\rangle|-\alpha\rangle$, becomes a crucial resource to link two computational bases of different nature [2].

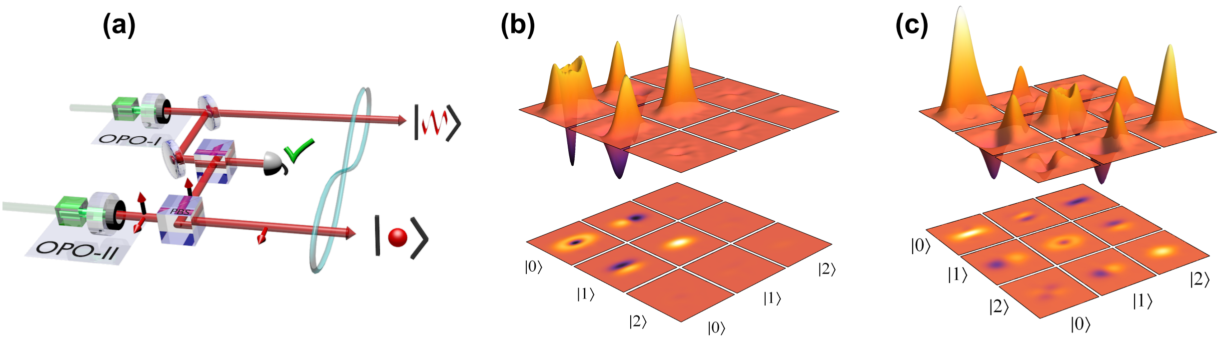

FIGURE 1: (a) Conceptual scheme for hybrid entanglement generation based on conditional measurement. (b) Hybrid entangled qubit state heralded by single-photon detection. (c) Hybrid entangled qutrit state heralded by two-photon detection. The blocks provide the Wigner functions associated with the reduced density matrices $\langle k|\hat{\rho}|l\rangle$ with $k, l \in \{0, 1, 2\}$.

We will report on the first generation of such hybrid entanglement between two remote nodes [3]. As shown in Figure 1(a), in one node we use a type-I continuous-wave optical parametric oscillator (OPO) to generate a single-mode squeezed vacuum. Subtracting a single-photon from this state would result in an odd coherent state superposition ($\alpha \approx 1$) [4]. On the other node, an EPR state is generated via a type-II OPO, which is used to generate a conditional single-photon state. Then two conditional beams are brought to interfere on a beam splitter in a indistinguishable way, which leads to the conditional generation of hybrid entanglement between two nodes. Figure 1(b) shows the constructed state after correcting 85% detection losses, which exhibits a fidelity 77±3% compared to the targeted state with $|\alpha| = 0.9$. The entanglement negativity is calculated to be 0.37 ± 0.01 (0.5 for ideal case).

Interestingly, a hybrid qutrit entanglement can be generated using exactly the same scheme but with a conditional detection of two photons. As shown in Figure 1(c), the diagonal blocks represent two-photon subtracted squeezed vacuum, one-photon subtracted squeezed vacuum, and squeezed vacuum, respectively. Such hybrid qutrit entanglement could be used to extend the hybrid quantum information processing to higher dimensions.

It is worth mentioning that in our experiment cavity and phase locking are performed by a simple and inexpensive technique based on a stand-alone microcontroller unit [5]. Such automatic digital locking not only eliminates the tedious work for re-engaging the locking, but also provides a stable performance in a long-term experiment. We will detail the general principle.

In summary, the work presented here constitutes the first demonstration of such hybrid entanglement enabling to link computational basis of different nature. This possibility, in combination with further works on high-fidelity quantum state engineering, opens the way to new optical hybrid architecture and quantum network operation based on heterogeneous systems.

[1] P. van Loock, "Optical hybrid approaches to quantum information", *Laser&Photon. Rev.* **5**, 167-200 (2011).
[2] U. L. Andersen, J. S. Neergaard-Nielsen, P. van Loock, A. Furusawa, "Hybrid quantum information processing", *arXiv :1409.3719*.(2014).
[3] O. Morin, K. Huang, J. Liu, H. Le Jeannic, C. Fabre, J. Laurat, "Remote creation of hybrid entanglement between particle-like and wave-like optical qubits", *Nature Photon.* **8**, 564-569 (2014).
[4] O. Morin, J. Liu, K. Huang, F. A. S. Barbosa, C. Fabre, J. Laurat, "Quantum state engineering of light with continuous-wave optical parametric oscillators", *J. Vis. Exp.* **87**, e51224 (2014).
[5] K. Huang, H. Le Jeannic, J. Ruaudel, O. Morin, J. Laurat, "Microcontroller-based locking in optics experiments", *arXiv :1409.3675*.(2014).

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Towards single-spin to microwave resonator coupling

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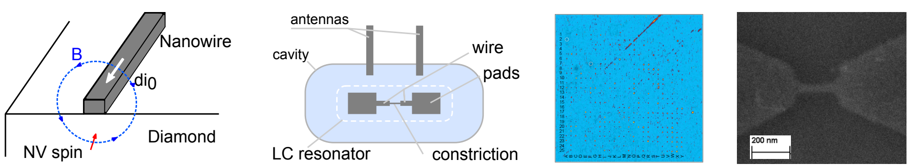
In recent years has emerged the field of hybrid quantum circuits that aims at combining the best of two worlds. On one hand, superconducting circuits are artificial atoms, which frequency and coupling to the microscopic environment can be engineered but they have relatively short coherence times. On the other hand microscopic systems, such as NV centers in diamond [1], have much longer coherence times, that can reach milliseconds or more even at room temperature. Recent experiments have shown that the reversible storage of a single microwave photon emitted by a superconducting qubit in an ensemble of NV centers is achievable, but unfortunately limited to a few hundreds of nanoseconds due to inhomogeneous broadening of the spin ensemble.[2]

Coupling only a single spin to the superconducting circuit would remove this limitation and allow for coherent manipulation of the spin via the microwave photons. With such a system we would be able to couple two distant spins via their interaction to the superconducting circuit.

Here we present our progress towards coupling a single-spin to a microwave resonator. We have concentrated our efforts on two kinds of spins, chosen for the large coherence times of their nuclear spins : NV centers in diamond and bismuth atoms in silicon [3]. Both systems present a nuclear spin of 1/2. We first aim to fabricate a high-quality factor linear superconducting resonator with a 15-nm-constriction aligned on top of the spin, implanted at 15-nm-depth in the host crystal (Fig 1). The magnetic field generated by such a nanowire will be high enough to achieve microwave detection of the spin in a few milliseconds. To obtain such a system several challenges have to be tackled : precise implantation of the spin with respect to alignment marks, accurate design and fabrication of the linear superconducting resonator to be as close as possible to the frequency of the spin and its location.



(a) (b) (c) (d)

FIGURE 1: Coupling between single spin and nanowire : (a)Coupling scheme between nanowire and spin implanted in host crystal, (b) Detection scheme for the superconducting resonator, (c) Implanted NV center pattern, detected by photoluminescence, (d)Nanowire fabrication in electronic lithography

[1] G. Balasubramanian and al., Nature Materials **8**, 383-387 (2009)

[2] Y. Kubo and al., Phys. Rev. Lett. **107**, 220501 (2011).

[3] G.Wolfowicz, and al.,Nature Nanotechnology **8**, 561âĂŞ564 (2013).

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Quantum dynamics simulator with the motional states of an ion in an anharmonic trap

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Following a recent proposal[1], we theoretically illustrate the possibility of using the motional states of a Cd+ ion trapped in an anharmonic potential to realize a quantum dynamics simulator of a single-particle Schrödinger equation. The anharmonicity renders the states energetically non equidistant and allows the control of population transfer between states with an electromagnetic field.
The simulated dynamics is discretized on spatial and temporal grids. The gate associated to an elementary evolution is estimated by the Split Operator formalism[2]. The radio-frequency field able to drive the corresponding unitary transformation among the qubit states encoded into the ion motional states is obtained by optimal control theory[3]. The field is unique for a given simulated potential. We also perform the computation of the field for the preparation of the initial simulated wave packet. This one needs to be adapted.
The stability of the optimal electric fields driving the elementary evolution is checked by performing dissipative Lindblad dynamics[4, 5] in order to consider fluctuations in the trap potential due to external fields[6].

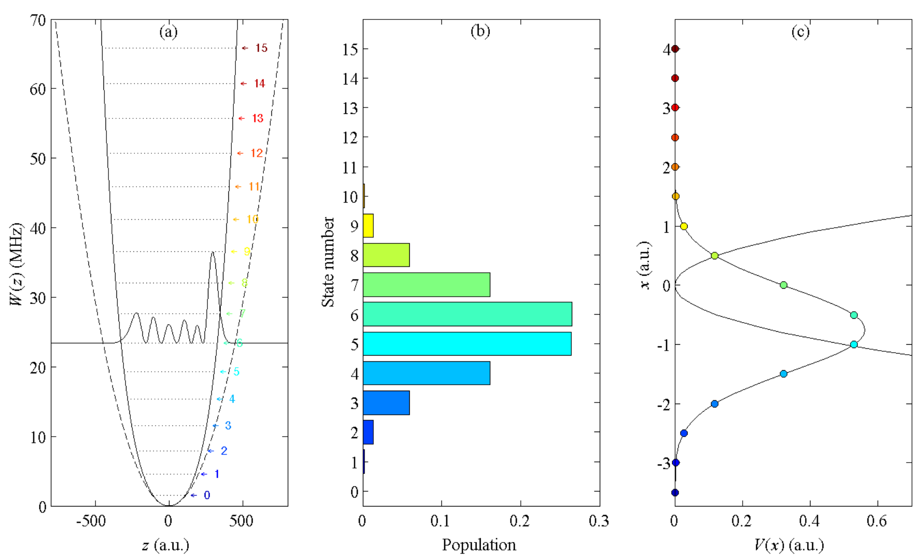

FIGURE 1: Mapping of the population in the motional states of the ion with the localization probability of the simulated wave packet

[1] L. Wang and D. Babikov, "Feasibility of encoding Shor's algorithm into the motional states of an ion in the anharmonic trap", J. Chem. Phys. **137**, 064301 (2012).
[2] M. D. Feit, Jr J. A. Fleck, and A. Steiger, "Solution of the Schrödinger equation by a spectral method", J. Comput. Phys. **47**, 412 (1982).
[3] W. Zhu, J. Botina and H. Rabitz, "Rapidly convergent iteration methods for quantum optimal control of population", J. Chem. Phys. **108**, 1953 (1997).
[4] G. Lindblad, "On the generators of quantum dynamical semigroups", Commun. Math. Phys. **48**, 119 (1976).
[5] W. Zhu and H. Rabitz, "Closed loop learning control to suppress the effects of quantum decoherence", J. Chem. Phys. **118**, 6751 (2003).
[6] S. Schneider and G. J. Milburn, "Decoherence and fidelity in ion traps with fluctuating trap parameters", Phys. Rev. A **59**, 3766 (1999).

Coherent Population Oscillation based storage in metastable Helium at room temperature

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The possible applications of quantum properties of light to communication, data processing or sensing aroused the interest for light-matter interaction, and one of the problems that must be addressed for such applications is the design of quantum memories. Different protocols have been developed to store light in atomic systems, such as Electromagnetically Induced Transparency (EIT) [1], Gradient Echo Memory [2] or non linear effects [3]. All these methods are based on the excitation of coherence between atomic levels and can thus be efficiently implemented only in systems where the coherence lifetime is long enough. They are thus very sensitive to dephasing effects such as magnetic field gradients.

On the contrary, Coherent Population Oscillations (CPO) gives rise to transmission resonances insensitive to field gradients. This phenomenon occurs in a two level system (TLS) when two coherent electromagnetic field of different amplitudes drive the same transition. The light beats modulate the population difference between the two levels and open a transparency window in the absorption profile of the weak field, limited by the decay rate of population of the upper level. As a population effect, CPO is usually not considered as a phenomenon that could be used to store a light field. Nevertheless, a new storage protocol based on Coherent Population Oscillation (CPO) was theoretically proposed for the implementation of spatial optical memories [4]. We report what is to our knowledge the first experimental demonstration of CPO-based storage. It is performed in hot metastable helium vapor, in a Λ system composed of two coupled TLSs, which gives rise to an ultranarrow CPO resonance due to the transfer of CPOs to CPOs between the lower states of the Λ-system [5].

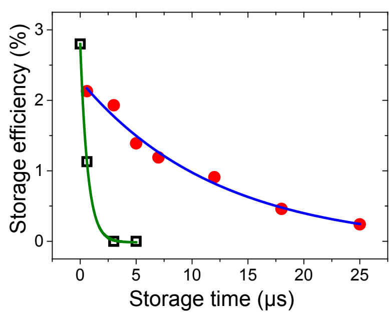

FIG. 1. Measured storage efficiency versus storage time for CPO (red dots) and EIT storage (open black squares) when the cell is at the edge of the magnetic shielding. CPO storage efficiency decreases with a $10\mu s$ time constant whereas for EIT storage, the time constant is less than $1\mu s$ (we checked that when the cell is in the shielding, both storage efficiencies decrease with the same time constant as function of storage time).

We compare CPO storage to EIT storage measurements which can also be performed in metastable helium [6]. We use the same storage sequences for both kinds of storage. We demonstrate that, contrary to EIT-based storage, CPO-based storage does not involve atomic coherences and it is thus robust to magnetic field gradients [7] (see fig.1). These results were also reproduced in Cesium vapor, in collaboration with the group of J. Tabosa (Brazil) [8]. Furthermore, this light storage technique is shown to be phase preserving.

[1] I. Novikova, R. L. Walsworth, and Y.Xiao, "Electromagnetically induced transparency-based slow and stored light in warm atoms", Laser Photonics Rev. **1**, 333-353 (2012).
[2] G. Hétet, M. Hosseini, B. M. Sparkes, D. Oblak, P. K. Lam, and B. C. Buchler, "Photon echoes generated by reversing magnetic field gradients in a rubidium vapor", Optics. Lett. **1**, 33 (2008).
[3] R. M. Camacho, P. K. Vudyasetu, and J. C. Howell, "Four-wave-mixing stopped light in hot atomic rubidium vapour", Nat. Photonics **1**, 3 (2009).
[4] A. Eilam, I. Azuri, A. V. Sharypov, A. D. Wilson-Gordon, and H. Friedmann, "Spatial optical memory based on coherent population oscillations", Optics Lett.**1**, 772 (2010).
[5] T. Lauprêtre, S. Kumar, P. Berger, R. Faoro, R. Ghosh, F. Bretenaker. and F. Goldfarb, "Ultranarrow resonance due to coherent population oscillations in a Λ-type atomic system", Phys. Rev. A **1**, 051805 (2012).
[6] M. A. Maynard, T. Labidi, M. Mukhtar, S. Kumar, R. Ghosh, F. Bretenaker, and F. Goldfarb, "Observation and measurement of an extra phase shift created by optically detuned light storage in metastable helium", EPL **1**, 44002 (2014).
[7] M. A. Maynard, F. Goldfarb, F. Bretenaker, "Light storage in a room temperature atomic vapor based on coherent population oscillations", arxiv:1406.3723.
[8] A. J. F. de Almeida, J. Sales, M.-A. Maynard, T. Lauprêtre, F. Bretenaker, D. Felinto, F. Goldfarb, and J. W. R. Tabosa "Light storage via coherent population oscillation in a thermal cesium vapor", accepted paper in Phys. Rev. A.

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Ultracold atoms in sub-wavelength optical lattice

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Cold atom systems used as quantum simulators offer an alternative to simulate many-body systems behavior (such as quantum hall effect, graphene, two-dimensional electron gases). Properties of condensed-matter systems (electrical conductivity, anti-ferromagnetism, etc) can be simulated with bosonic and fermionic atoms in optical lattices [1, 2]. This so called quantum simulator benefits of optical lattices highly tunable parameters : lattice geometry, potential well depth, bosonic or fermionic nature of atoms, sign and intensity of atomic interactions,etc. Optical lattice is a strong tool. The common approach for generating optical lattices is interfering two laser beams in one dimension. But in our new project, we are going to produce lattice by irradiating a nanostructure gold layer. Layer tunability allows producing complex lattice geometries, especially for hexagonal lattice.

[1] Bloch, I., Nature Physics, Volume 1, p. 23, 2005.

[2] Esslinger, T., Annual Review of Condensed Matter Physics, volume 1, p. 129- 152, 2010.

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Quantum thermal machines with single nonequilibrium environments

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We propose a scheme for a quantum thermal machine made by atoms interacting with a single non-equilibrium electromagnetic field. The field is produced by a simple configuration of macroscopic objects held at thermal equilibrium at different temperatures. We show that these machines can deliver all thermodynamic tasks (cooling, heating and population inversion), and this by establishing quantum coherence with the body on which they act. Remarkably, this system allows to reach efficiencies at maximum power very close to the Carnot limit, much more than in existing models. Our findings offer a new paradigm for efficient quantum energy flux management, and can be relevant for both experimental and technological purposes.

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Detector Device-Independent Quantum Key Distribution

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Quantum key distribution (QKD) enables the exchange of provably secure cryptographic keys between two spatially separated users, Alice and Bob, who are connected by a potentially insecure quantum channel. However, despite the prowess of QKD, one still has to be prudent about potential side-channel attacks that may lead to security failures.To deal with detector side-channel attacks, researchers recently proposed measurement-device-independent QKD (mdiQKD) [1]. In the scheme, Alice and Bob each randomly prepare one of the four BB84 states and send it to a third party, Charlie, who purportedly performs a Bell-state-measurement on them. Seen in this light, it is clear that Alice and Bob do not have to trust Charlie since any other non-entangling measurement would necessarily introduce some noise between them. Therefore, mdiQKD offers information-theoretic security against all possible detector side-channel attacks. However, there are still some technical challenges in implementing mdiQKD, especially in the case of the Bell-state-measurement where the interference of two independent laser sources is critical for good secret key rates.

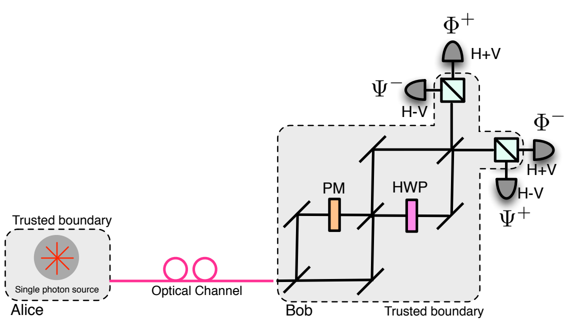

FIG. 1. The scheme uses single photons to carry Alice' and Bob's qubits. Specifically, Alice encodes her qubit into a single photon and then sends it to Bob who attaches a second qubit that resides in another degree-of-freedom. Here, Alice uses polarization encoding, i.e., $\{|H+V\rangle, |H-V\rangle, |H+iV\rangle, |H-iV\rangle\}$, to encode her qubit and Bob uses spatial encoding, i.e., $\{0, \pi/2, \pi, 3\pi/2\}$ to encode his qubit. This is implemented using the first interferometer with phase modulator (PM). Then, to correlate their qubits, Bob performs an entangling measure on them using a linear-optical BSM where the involved single-photon detectors can be omitted from the security analysis.

In this abstract, we propose a novel QKD scheme whose security is independent of detector side-channel attacks and importantly only requires single-photon interference. This is achieved by exploiting the single-photon-two-qubit (SPTQ) concept, i.e., we use single-photon light states as physical couriers to carry Alice' and Bob's qubits. The scheme is illustrated in FIG. 1. Additionally, to demonstrate the feasibility of the scheme, we implemented a proof-of-principle experiment similar to test the theoretical predictions and analyze the detection outcomes for all of the combination of Alice and Bob's settings, we fixed the state prepared by Alice and scanned the phase of Bob's interferometer with a phase modulator. See Fig. 2 for the experimental curves.

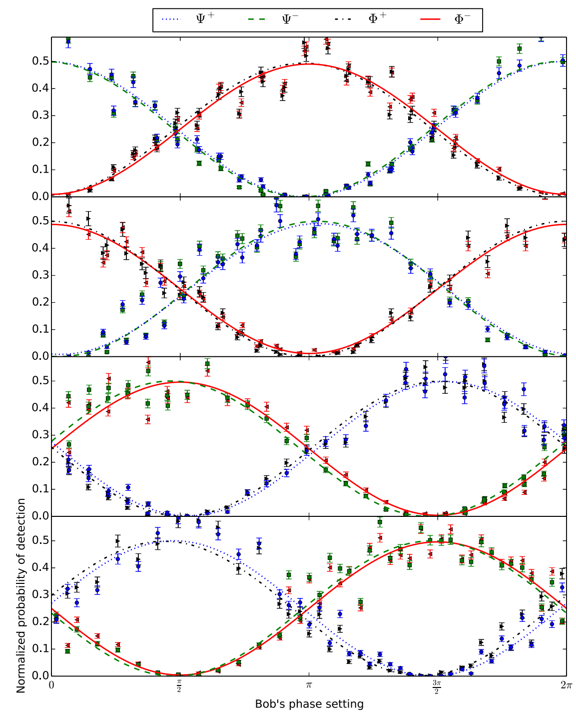

FIG. 2. Experimental detection probabilities for the four states prepared by Alice (+, -, +i, -i, top to bottom) versus the phase setting of Bob's interferometer. Note that in each subplot, the four curves are given by the corresponding Bell state projections.

[1] H.-K. Lo, M. Curty and B. Qi, Phys. Rev. Lett. **108**, 130503 (2012).

Sub-shot noise interferometry in lattice

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We study the possibility to create entangled states in an optical lattice in order to realize a sub-shot noise clock measurement. We propose a simple way to create entanglement between the different wells with a beam splitter between these wells. We then study this entanglement and more specifically the possibility tu use it to implement a sub-shot noise measurement of the clock transition in each well. To characterize the entanglement between wells we use the quantum Fisher information as defined in [1]. In the classical case, this Fisher information is lower or equal to N, N being the number of particles involved. As a consequence, a necessary and sufficient condition to realize a sub-shot noise measurement J is simply expressed as

$$F_Q[\rho_{in}, J] > N$$

with ρ_{in} representing the density operator of the initial state [2]. In a second time, we then investigate the source of the entanglement obtained starting from the hypothesis of a transfer of entanglement between particles to modes.

[1] S. L. Braunstein and C. M. Caves, Phys. Rev. Lett. **72**, 3439 (1994).
[2] L. Pezzé, and A. Smerzi, Phys. Rev. Lett. **102**, 100401 (2009).

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Quantum statistics of light transmitted through an intracavity Rydberg medium

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In an optically non-linear atomic medium, dispersion and absorption of a classical light beam depend on powers of its amplitude. At the quantum level, dispersive optical non-linearities translate into effective photon-photon interactions, which potentially allow to implement photonic conditional two-qubit gates. The standard Kerr dispersive non linearities obtained in non-interacting atomic ensembles, either in off-resonant two-level or resonant three-level configurations involving Electromagnetically Induced Transparency (EIT), are too small to allow for quantum non-linear optical manipulations. To further enhance such non-linearities, EIT protocols were put forward in which the upper level of the ladder is a Rydberg level. In such schemes, the strong van der Waals interactions between Rydberg atoms result in a cooperative Rybderg blockade phenomenon [1], where each Rydberg atom prevents the excitation of its neighbors inside a blockade sphere. This Rydberg blockade deeply changes the EIT profile and leads to magnified non-linear susceptibilities [2, 3]. In particular, giant dispersive non-linear effects were experimentally obtained in an off-resonant Rydberg-EIT scheme using cold rubidium atoms placed in an optical cavity [4]. In the work presented here, we theoretically investigate the quantum statistical properties of the light generated in this protocol by computing the steady-state second-order correlation function. Our simulations suggest that the bunched or antibunched nature of the outgoing light and its coherence time may be controlled by adjusting the detuning between the cavity mode and probe field frequencies.

[1] M. D. Lukin *et al.*, Phys. Rev. Lett. **87** 037901 (2001).
[2] T. Peyronel *et al.*, Nature **488** 57 (2012).
[3] D. Maxwell *et al.*, Phys. Rev. Lett. **110** 103001 (2013).
[4] V. Parigi *et al.*, Phys. Rev. Lett. **109** 233602 (2012).

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10 GHz working regime heralded telecom single photon source

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Generally, in most of quantum optics experiments, pairs of telecom photons originate from the non-linear conversion of optical pulses at $\approx$ 780 nm generated by solid state mode-locked lasers [1] with repetition rate limited to few hundreds of MHz. Conversely, ultra-fast fiber lasers with repetition rates up to a few tens of GHz are readily available in the C-band of telecom wavelengths. At the same time, highly efficient periodically poled lithium niobate waveguides (PPLN/w) can be combined to obtain a cascade non-linear processes. We propose here to exploit both state-of-the-art telecom laser technology and guided-wave non linear optics for generating telecom entangled photon at the ultra-high repetition rates : in our scheme, optical pulses emitted by a fiber laser with a repetition rate of 10 GHz are sent to a PPLN/w to be converted from 1540 nm to 770 nm via second-harmonic generation (SHG), and then used to pump a second PPLN/w so as to generate, via spontaneous parametric down conversion (SPDC), photon pairs at 1540 nm. Subsequently, the paired photons are deterministically separated using a combination of a wavelength division multiplexer (DWDM) and a fiber Bragg grating (FBG) filter, in complementary standard telecom channels (ITU 43 and ITU 50).

We characterized the quality our source with a conditional scheme : the detection of photons in one channel, performed by a superconducting single photon detector (SSPD), able to handle 10 GHz repetition rate, will herald the presence of complementary photon in the other arm of the setup : the scheme is an implementation of an "heralded single photon source" (HSPS). The use of a 10 GHz pulsed laser associated with non-linear optics and of standard, high-performance telecom components allows us obtaining high quality heralded photons at a high rate and with negligible multi-photon events. More specifically, in our experiment, single photons at 1540 nm are announced with an heralding efficiency of $\approx 40\%$. Thanks to the laser high repetition rate, we observe heralding rate as high MHz while keeping the mean number of photon-pairs generated per pump pulse well below 0.1. This result is confirmed by a standard Hanbury Brown and Twiss (HBT) measurement who certifies the high quality of our single photons in terms of the autocorrelation function $g^{(2)}(0)$, namely of the (low) probability of unwanted multi-pairs events against single-photon pair ones.

These performances are crucial ingredients demanded for both fast and secure quantum communication protocols and make our source a promising candidate for future quantum networking applications. To conclude we stress that the implemented configuration is highly suitable to long distance entanglement teleportation [2], where a common telecom laser emitting optical pulses at 1550 nm can be distributed to two remote locations and locally used to generate via SPDC photon-pairs with high timing accuracy. In this framework, high repetition rate telecom lasers act as a tool for fighting the low success rates of the quantum protocols due to probabilistic photon pair generation via SPDC process in suitable non-linear crystals. So far, promising results have been obtained, gauging the quality of our approach. Next step is to perform a two-photon interference experiment with GHz repetition rates. This should demonstrate the effectiveness of our high-speed photon pair sources for practical quantum teleportation operation.

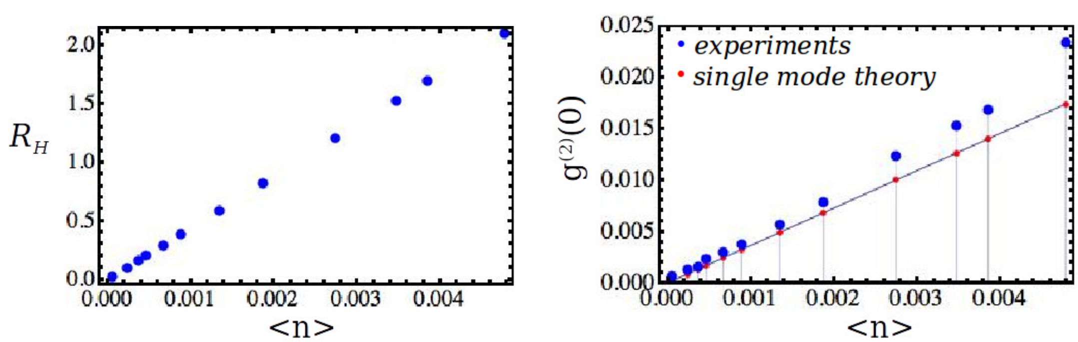

FIGURE 1. (Left) : Recorded heralding rate R_H (in MHz) are shown as a function of mean photon pairs per pulse, visualizing the importance of high repetition rate working regime. (Right) : Second order auto-correlation function which quantifies the "singleness" of the emitted single photons. Our ultra-fast HSPS are capable of delivering, at such high corresponding heralding rates, high probability of single photons contribution compared to unwanted multi photons events.

[1] P. Aboussouan *et al.*, Phys. Rev. A, **81**, 021801, (2010).

[2] R. Kaltenbaek *et al.*, Phys. Rev. A, **79**, 040302, (2009).

Provably Secure and Practical Quantum Key Distribution over 307 km of Optical Fibre

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Quantum key distribution (QKD) enables the distribution of provably secure shared bit strings. Since the first theoretical conception, a wide variety of QKD implementation have been demonstrated. However, the operating distance of practical fibre-based QKD systems is limited to about 150 km, which is mainly due to the high background noise produced by commonly used semiconductor single-photon detectors (SPDs) and the stringent demand on the minimum classical-post-processing (CPP) block size.

In order to achieve long-distance QKD, existing systems resort to using superconducting nanowire single-photon detectors (SNSPD), which is a natural choice of detector for state of the art laboratory based experiments due to their capability of operating with extremely low dark count rates. However, practical considerations would prohibit their use in compact commercial systems due to the requirement for cryogenic temperatures (typically <3 K). In addition, all record-distance demonstrations [1] to date have ignored corrections due to finite-length keys ; in particular, it has been shown that corrections due to finite-length keys are non-negligible for realistic CPP block sizes. This means that previous QKD demonstrations might be overly optimistic in the achievable distance, if a scientifically quantifiable security parameter was to be calculated. Indeed, taking these effects into account is challenging for record-distance experiments since the time required to fill the CPP block becomes very long, due to low detection rates, requiring a very stable system.

In this work we demonstrate a robust and autonomous QKD system, based on practical and compact InGaAs SPDs, which achieves secure key distribution over 307 km. This is an increase of almost a factor of two compared to the previous maximum distance with InGaAs detectors. One of the enabling factors was our recent demonstration of free-running InGaAs SPDs operating with dark count rates (DCR) as low as 1 Hz at 10% efficiency [2], which is a reduction of over two orders of magnitude compared to previous InGaAs SPDs. Moreover, we have sharpened the finite-key security analysis, which improves the performance of the QKD protocol when using small CPP block sizes. This has enabled us to provide a quantifiable security parameter for the complete protocol ($\epsilon_{\text{qkd}} = 4 \times 10^{-9}$), which has not been possible before for QKD systems operating over 150 km. One of our main contributions is the derivation of a new tail inequality used during the parameter estimation stage. The tail inequality allows the minimum CPP block size to be reduced by around an order of magnitude (to about $10^4 - 10^5$).

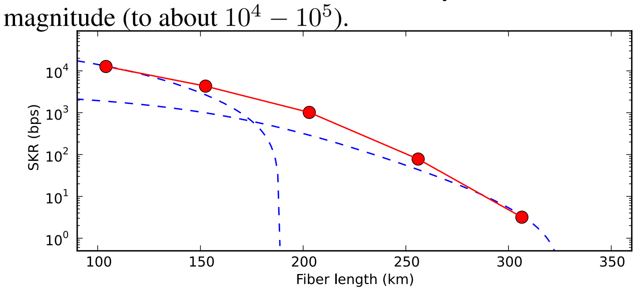

FIGURE 1. Experimental final secret key rate versus fibre length. Theoretical plots (dashed) for two SPD temperatures, 223 K (left) and 153 K (right).

The QKD system uses the coherent one-way protocol and runs at a clock rate of 1.25 GHz [3]. The optical fibre used in this work has a record low average attenuation of 0.160 dB/km (standard SMF typically has 0.2 dB/km), making it possible to extend the maximum achievable distance significantly. Figure 1 shows the secret key rates achieved at different fibre lengths. We found that the optimum operating temperature of the SPDs changes with attenuation in the quantum channel due to a trade-off between the DCR and afterpulsing. At the maximum distance, the optimum detector temperature was 153 K, achieved with a compact stirling cooler, which is significantly more practical than using SNSPDs. This work demonstrates that practical QKD is feasible over very long distances even with standard telecom components and rack mounted architecture, whilst maintaining a quantifiable statement for the failure probability of the protocol.

[1] B. Korzh et al., "Provably Secure and Practical Quantum Key Distribution over 307 km of Optical Fiber," Preprint arXiv :1407.7427 (2014).
[2] B. Korzh, N. Walenta, T. Lunghi, N. Gisin, and H. Zbinden, "Free-running InGaAs single photon detector with 1 dark count per second at 10% efficiency," Applied Physics Letters 104, 081108 (2014).
[3] N. Walenta et al. "A fast and versatile quantum key distribution with system with hardware key distillation and wavelength multiplexing," New Journal of Physics 16, 013047 (2014).

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Parametric amplifier based on a voltage biased Josephson junction

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Recently, microwave amplifiers based on superconducting circuits instead of semiconductors have reached noise levels very close to the quantum limit [1, 2] but they are difficult to handle because of a severe gain-bandwidth trade-off and very small dynamic range.

Recent experiments with superconducting circuits consisting of a dc-voltage biased Josephson junction in series with a resonator, showed that a tunneling Cooper pair can emit two photons in different modes with a total energy of $2e$ times the applied voltage [3]. We show transmission measurements on the device in [3], indicating amplification.

A theoretical analysis shows that this circuit can indeed operate as Josephson parametric amplifier with high gain with the energy of a Cooper pair playing the role of the pump and the Josephson junction the role of linear medium. Interestingly, this amplifier has a different trade-off between gain and dynamic range : In existing JPAs the junction should be small to be as non-linear as possible, but large in order to handle large signals, whereas in our case, a larger junction size increases both gain and dynamic range. Therefore it might be easier to combine high gain, high bandwidth and high dynamic range.

[1] C. Caves et al., "Quantum limits on noise in linear amplifiers " , PRD **26**, 1817 (1982).
[2] N. Bergeal et al., "Phase-preserving amplification near the quantum limit with a Josephson ring modulator", Nature **465**, 64 (2010).
[3] M. Hofheinz et al., "Bright side of the Coulomb Blockade" , PRL **106**, 217005 (2011).

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Finite temperature reservoir engineering and entanglement dynamics

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

Coherence control in rare-earth-ion doped crystals

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Light-matter interaction is a key element of quantum communication and quantum information. One implementation, quantum memories can be used in a repeater for communication and even as a transducer between flying and stationary qubits. Requirements for such devices includes high efficiency and long coherence time. Here we concentrate on extending the coherence time.

Promising candidates for such devices are rare-earth-ion doped crystals thanks to their atomic-like energy structure and their long optical and spin coherence times.

We present here a spectroscopic study of the hyperfine transitions in ^{151}Eu:Y_2SiO_5 under a magnetic field. A magneto-optical technique called Raman heterodyne scattering is employed to characterize the spin transitions and coherence time of our sample. We extend the coherence time using two different methods.

The first method uses a static magnetic field to find transitions more robust to external perturbations. By carefully choosing the strength and orientation of the magnetic field, the fluctuations of the local magnetic environment can be decreased. This extends the coherence time by at least one order of magnitude.

The second approach is based on dynamical decoupling (DD) techniques[1], inspired by experiments done in the research field of NMR. This technique actively drive the ions against the environment fluctuations. A sequence of radiofrequency pulses are applied to the crystal to refocus the spin of the ions faster than the interactions timescale with the environment. We employed a Carr-Purcell-Meiboom-Gill (CPMG) sequence, which allows us to extend the coherence time of our sample to the minute regime by sending more than 60000 RF π-pulses.

By combining these two approaches, we demonstrate a coherence lifetime of more than one minute which is four order of magnitude longer than the natural coherence time of the transition. These techniques can be implemented for different quantum memory protocol such as electromagnetically induced transparency (EIT)[2,3], controlled reversible inhomogeneous broadening (CRIB)[4]and the atomic frequency comb (AFC)[5].

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[1] J. J. Longdell, E. Fraval, M. J. Sellars, and N. B. Manson. Stopped light with storage times greater than one second using electromagnetically induced transparency in a solid. *Phys. Rev. Lett.*, 95(063601), 2005.

[2] T. Chanelière, D. N. Matsukevich, S. D. Jenkins, S.-Y. Lan, T. A. B. Kennedy, and A. Kuzmich. Storage and retrieval of single photons transmitted between remote quantum memories. *Nature*, 438(7069):833–836, 2005.

[3] M. D. Eisaman, A. Andre, F. Massou, M. Fleischhauer, A. S. Zibrov, and M. D. Lukin. Electromagnetically induced transparency with tunable single-photon pulses. *Nature*, 438(7069):837–841, December 2005.

[4] A.L. Alexander, J.J. Longdell, M.J. Sellars, and N.B. Manson. Coherent information storage with photon echoes produced by switching electric fields. *Journal of Luminescence*, 127(1):94 – 97, 2007.

[5] M. Afzelius, C. Simon, H. de Riedmatten, and N. Gisin. Multi-mode quantum memory based on atomic frequency combs. *Phys. Rev. A.*, 79:052329, 2009.

Towards a loophole-free Bell test with spin qubits in diamond

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Entanglement is one of the most intriguing phenomena in quantum physics, especially when it comes to space-like separated objects. Indeed, the outcomes of independent measurements on entangled objects can reveal strong correlations that can not be explained by classical physics or any other local realistic model. The violation of Bell's inequalities provides the ultimate test of local realism [1]. Yet to date, no Bell test has been performed while closing the two main loopholes of detection and locality at the same time.

Here, we will present our latest results towards this goal of a loophole-free Bell test. Our quantum system consists of the electronic spin associated with single NV center defects in diamond. We use a heralded entanglement protocol recently demonstrated in our group [2] to generate an entangled state between a pair of NV centers located in two laboratories separated by 1.3 km and connected via an optical fiber. The moderate time (<3 us) required for high fidelity (>99%) qubit rotations and efficient (>97%) readout [3] could allow the experimental violation of Bell's inequalities between two space-like separated entangled spins without the fair sampling assumption.

Besides being of fundamental interest, experiments violating Bell's inequalities are at the root of proposed protocols for device independent quantum key distribution [4] and randomness amplification [5].

[1] J.S. Bell, *Physics* **1**, 195-200, (1964).
[2] H. Bernien *et al.*, *Nature* **497**, 86-90 (2013).
[3] L. Robledo *et al.*, *Nature* **574**, 477 (2011).
[4] J. Barrett *et al.*, *Phys. Rev. Lett.* **95**, 010503 (2005).
[5] S. Pironio *et al.*, *Nature* **464**, 1021-1024 (2010).

Macroscopic polarization rotation induced by a single confined spin

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Single photons are nearly ideal flying quantum bits, and the major challenge that optical quantum computing must face is to engineer photon-photon interactions. A promising way to do so is to implement an efficient spin-photon interface making use of the polarization rotation (so-called Faraday or Kerr rotation) induced by a single spin. Observations of Kerr rotation induced by a single spin were reported only recently, with rotation angles in the few 10^{-3} degree range.

Here, cavity-QED effects are used to demonstrate a Kerr rotation by several degrees with a single solid-state spin [1]. A single quantum dot spin is inserted inside a micropillar, a geometry which currently constitutes the most efficient photonic interface between an external laser beam and a confined cavity mode [2,3,4].

A macroscopic Kerr rotation of ±6° (depending on the spin state) is demonstrated for the reflected probe beam. This macroscopic rotation is reached thanks to two main features. The first one is the exaltation of the spin photon-interaction induced by the optical confinement. The second feature is the efficient interference between the directly-reflected light and the light injected into and re-extracted from the cavity (see Fig. 2b).

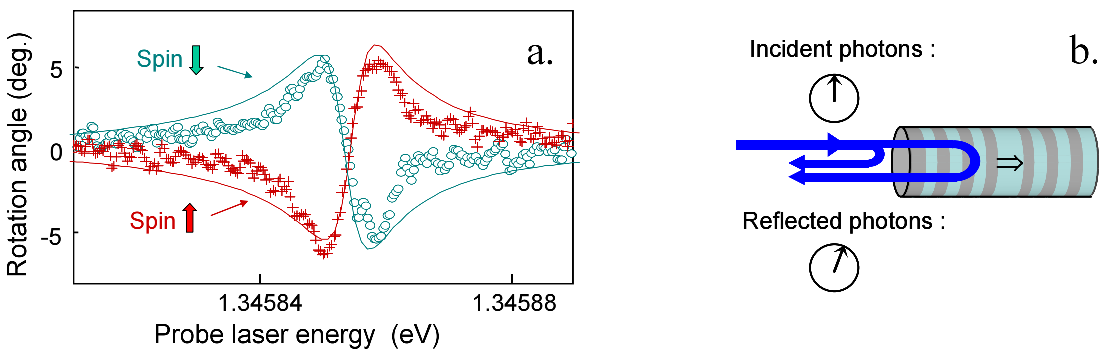

Fig.2. **a)** Demonstration of giant Kerr rotation induced by a single spin. The spin state is pumped in the up or down state by a resonant pump beam with L or R polarization. A spin-dependent Kerr rotation up to ±6° is observed. **b)** Polarization states for the incident and reflected beams.

This novel way of interfacing a flying qubit and a solid-state quantum memory opens the road for a wide range of applications for quantum information processing and long-distance quantum communication.

[1] A. Dousse, L. Lanco, J. Suffczynski, E. Semenova, A. Miard, A. Lemaître, I. Sagnes, C. Roblin, J. Bloch, and P.Senellart, "Controlled light-matter coupling for a single quantum dot embedded in a pillar microcavity using far-field optical lithography", Phys. Rev. Lett. **101**, 267404 (2008).
[2] C. Arnold, V. Loo, A. Lemaître, I. Sagnes, O. Krebs, P. Voisin, P. Senellart and L. Lanco, "Optical bistability in a quantum dots/micropillar device with a quality factor exceeding 200 000", Appl. Phys. Lett. . **100**, 111111, (2012)
[3] V. Loo, C. Arnold, O. Gazzano, A. Lemaître, I. Sagnes, O. Krebs, P. Voisin, P. Senellart and L. Lanco, "Optical nonlinearity for few-photon pulses on a quantum dot-pillar cavity device", Phys. Rev.Lett. **109**, 166806, (2012)
[4] C. Arnold, V. Loo, A. Lemaître, I. Sagnes, O. Krebs, P. Voisin, P. Senellart, and L. Lanco, "Cavity-enhanced real-time monitoring of single-charge jumps at the microsecond time scale", Phys. Rev.X. **4**, 021004, (2014).

Practical sharing of quantum secrets over untrusted channels

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In this work we address the issue of sharing a quantum secret over untrusted channels between the dealer and players. Existing methods require entanglement over a number of systems which scale with the security parameter, quickly becoming impractical. We present protocols (interactive and a non-interactive) to share a quantum secret state such which is secure even in the presence of malicious parties, where single copy encodings are sufficient. Our protocols work for all quantum secret sharing schemes, and are implementable with current experimental set ups. For a single authorised player, our protocols act as quantum authentication protocols.

In secret sharing a dealer wishes to distribute a secret to a network of players such that only authorised sets of players can access the secret, and unauthorised sets of players cannot. After the initial protocols for sharing classical secrets [1, 2], ones for sharing quantum secrets have recently emerged [3, 4], and have found uses including secure multiparty computation [5]. However, these protocols rely on trusted channels between the dealer and the players. In practice channels may be corrupted either by unavoidable noise, or malicious attacks.

One way to resolve this situation would be to use the quantum authentication protocol [6]. However this protocol is highly impractical in that it uses error correcting codes and which would require encoding each qubit sent from the dealer into a highly entangled state (or perform entangling measurements, which would allow the generation of large entangled states), the size of which scale with the security parameter. This difficulty, on a par with the coherences needed for full scale quantum computing, renders this approach infeasible in the near future.

Here, we present a protocol which is universal (it works for all quantum secret sharing protocols) and is implementable with current experimental setups, for example by using graph states [7, 8]. This is possible because our protocol uses only single copy encodings.

[1] A. Shamir, Commun. ACM 22, 612 (1979).
[2] G. R. Blakley, Proceedings of the National Computer Conference 48, 313-317 (1979).
[3] M. Hillery, V. Bužek and A. Berthiaume, Phys. Rev. A 59, 1829 (1999).
[4] R. Cleve, D. Gottesman, H.K. Lo, Phys. Rev. Lett. **83**, 648 (1999).
[5] M. Ben-Or, C. Crépeau, D. Gottesman, A. Hassidim, A. Smith, In 47th Annual IEEE Symposium on Foundations of Computer Science, FOCS'06, 249-260. (2006).
[6] Howard Barnum, Claude Crépeau, Daniel Gottesman, Adam Smith and Alain Tapp, Proc. 43rd Annual IEEE Symposium on the Foundations of Computer Science (FOCS '02), pp. 449-458. IEEE Press, (2002).
[7] D. Markham and B. C. Sanders, Phys. Rev. A, **78**(4) 042309 (2008).
[8] B. A. Bell, D. A. Herrera-Martí, M. S. Tame, D. Markham, W. J. Wadsworth, J. G. Rarity Nature Communications 5, 3658 (2014)

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On-demand light storage at the single photon level in the millisecond regime

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Quantum cryptography is one of the best scheme for secure communication [1]. The main problem is that photon propagation in an optical fiber suffers from loss over long distances. Communication protocol based on quantum repeater [2] allows long distance quantum communication. To realise such a quantum repeater, it is necessary to have a quantum memory.

To implement such a device, rare-earth doped crystals are very good candidates. Indeed, On-demand storage at the single photon level [3], storage time of minutes [4], cavity-enhanced storage [5] and multimode storage [6] have already been demonstrated in those materials. However, all of these results have to date not been combined in a single experiment.

We use the atomic frequency comb (AFC) quantum memory protocol [7] in a europium doped crystal (Eu :YSO) absorbing at 580 nm. The energy structure of europium allows us to perform the on-demand AFC protocol [7] which requires three energy separated ground states.

In this work, we demonstrate a single photon level storage using the spin refocusing technique [8] for storage time extension. The spin refocusing sequence is basically a series of radio frequency population inversion pulses for the spin transition. These pulses swap back and forth a single spin excitation delocalized over an ensemble with a highly populated state. As a consequence, the sequence would induce easily some noise if it does not reach high inversion efficiency. The challenge is to produce such an efficient sequence and filter the noise produced by residual imperfections.

So, the key point of this experiment is noise filtering. For instance, we use spatially separated laser beam for spatial filtering and a Fabry-Pérot cavity for frequency filtering. We also introduced optical pumping sequences to limit the fluorescence noise.

Here, we report an on-demand storage of two modes at the single photon level ($|\alpha|^2 = 1$ for each mode) of 0.5 ms with an efficiency of 3 $\%$ and a signal to noise ratio (SNR) between 1 and 2 depending on the mode. In a preliminary experiment, storage of five modes at the single photon level has also been demonstrated with an SNR approaching 1. This is the first time on-demand single photon level storage has been realised in a solid-state material at this time scale.

These results pave the way to realise the AFC DLCZ protocol [9] and so, build a quantum repeater link.

[1] Gisin, N., Ribordy, G., Tittel, W., and Zbinden, H. *Rev. Mod. Phys.* **74**(1), 145–195 Mar (2002).
[2] Briegel, H.-J., Dür, W., Cirac, J. I., and Zoller, P. *Phys. Rev. Lett.* **81**(26), 5932–5935 Dec (1998).
[3] Timoney, N., Usmani, I., Jobez, P., Afzelius, M., and Gisin, N. *Phys. Rev. A* **88**(2), 022324 August (2013).
[4] Heinze, G., Hubrich, C., and Halfmann, T. *Phys. Rev. Lett.* **111**, 033601 Jul (2013).
[5] Jobez, P., Usmani, I., Timoney, N., Laplane, C., Gisin, N., and Afzelius, M. *New Journal of Physics* **16**(8), 083005 (2014).
[6] Usmani, I., Afzelius, M., de Riedmatten, H., and Gisin, N. *Nat Commun* **1**, 12– April (2010).
[7] Afzelius, M., Simon, C., de Riedmatten, H., and Gisin, N. *Phys. Rev. A* **79**(5), 052329 May (2009).
[8] Alexander, A. L., Longdell, J. J., and Sellars, M. J. *J. Opt. Soc. Am. B* **24**(9), 2479–2482 September (2007).
[9] Sekatski, P., Sangouard, N., Gisin, N., de Riedmatten, H., and Afzelius, M. *Phys. Rev. A* **83**, 053840 May (2011).

Coherent manipulation of Andreev bound states

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Superconducting qubits based on Josephson junctions are widely used in solid-state quantum information experiments. These qubits exploits the non-linear current-phase relation of the Josephson effect. According to the microscopic description of the Josephson effect, the supercurrent is carried by pairs of Andreev bound states that form two-level systems (TLS) localized at the junction. Yet the current-phase relation exploited by Josephson qubits corresponds only to the ground state of these TLS.

In this work, we probe all the states of unique Andreev pair TLS on the simplest Josephson junction: a single-atom contact. This contact is inserted in a superconducting loop coupled to a microwave resonator. This standard circuit-QED architecture allows us to measure the state of this TLS in a single shot, to manipulate it coherently, measure its excited state lifetime $T_1 = 4\,\mu$s, and its coherence time $T_2^* = 20\,\mathrm{ns}$. Besides, poisoning of the TLS by out-of-equilibrium quasiparticles is observed.

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

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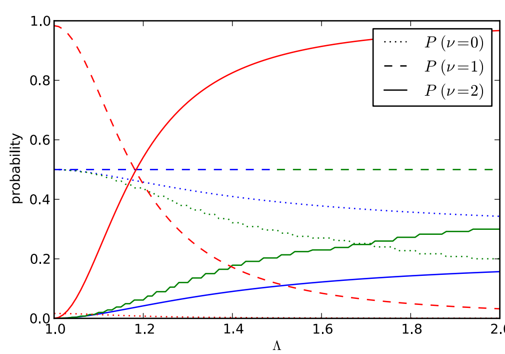
An atomic ensemble optically driven on a transition towards a Rydberg level exhibits complex many-body dynamics, due to the induced strong dipole-dipole interactions. In particular, these interactions prevent two atoms from being simultaneously excited to their Rydberg state when located close to each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

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

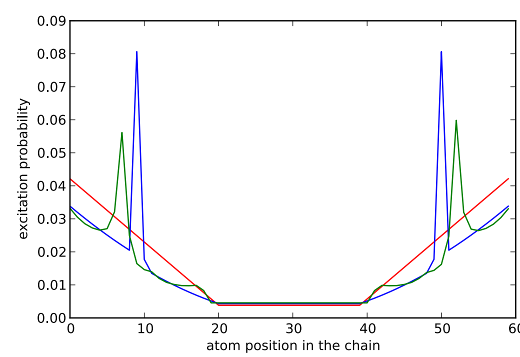
In this work, we keep the first assumption (sharp blockade radius) to study the dynamics of a dense 1D few-R_b-long atomic chain and test the validity of the second approximation (thermalization). We provide an analytical description of the emergent excitation lattice in the thermalization framework,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

A numerical diagonalization of our system's Hamiltonian ($N = 60$), however, allows us to show noticeable differences in the excitation number probability as well as the spatial distribution of Rydberg excitations compared to the thermalization hypothesis. A 5-dimensional toy-model of the system confirms that these differences are not a numerical artifact.

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



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



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

[1] M. Saffman, T. G. Walker, and K. Mølmer, "Quantum information with Rydberg atoms", Rev. Mod. Phys. **82**, 2313 (2010).
[2] Igor Lesanovsky, Beatriz Olmos, Juan P. Garrahan, "Thermalization in a Coherently Driven Ensemble of Two-Level Systems", Phys. Rev. Lett. **105** 100603 (2010)
[3] S. Bettelli, D. Maxwell, T. Fernholz, C. S. Adams, I. Lesanovsky, C. Ates, "Exciton dynamics in emergent Rydberg Lattices", Phys. Rev. A **88**, 043436 (2013).

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Dopper and sub-Doppler cooling of metastable Helium-4 :
Towards probing momentum-space correlations of ultracold lattice gases

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Within the growing pantheon of atoms which have been cooled to ultracold temperatures, Helium holds a special place due to its many peculiar properties. The large internal energy of the long-lived 2^3S_1 metastable state allows for single atom detection with micro-channel plate detectors (MCP), and has led to the direct observation of fundamental effects such as bunching and anti-bunching of bosons and fermions [1]. At the Laboratoire Charles Fabry, we are developing a new apparatus for the study of many-body states of ultracold Helium in an optical lattice, in particular to study the correlations at the critical points of the finite-temperature Bose-Hubbard model. The MCP and long 300 ms time-of-flight of the apparatus will allow us to probe momentum-space correlations due to quantum depletion and formation of particle-hole pairs [2]. As we work towards this goal, we are exploiting some of the other odd properties of Helium to perform novel studies in laser cooling.

We have recently demonstrated three-dimensional cooling of metastable Helium-4 in a purely Doppler regime, finding quantitative agreement with Doppler theory [3]. Despite the central role it plays in laser cooling and the study of ultracold atoms, to our knowledge, such a demonstration has never been reported, largely due to the presence of sub-Doppler mechanisms in atoms with a degenerate ground-state manifold. With Helium, the light mass, and relatively narrow transition linewidth result in a small capture velocity, strongly inhibiting sub-Doppler cooling on the usual $2^3S_1 \rightarrow 2^3P_2$ cycling transition. While the capture velocity range can in principle be enhanced with higher cooling beam intensities, it has been shown that the cooling becomes less efficient in the limit of high intensities, as multi-photon effects become more important [4].

On the other hand, the effects that limit intensities on the red side of the $2^3S_1 \rightarrow 2^3P_2$, are expected to aid in cooling on the blue side of the $2^3S_1 \rightarrow 2^3P_1$ [5]. On this transition, Sisyphus cooling is assisted by the presence of a dark state, and is thus referred to as *gray* molasses cooling [6]. We have demonstrated gray molasses cooling of a cloud of atoms to temperatures as low as 10 μK (5 times the recoil temperature), while we are able to cool to 15 μK with near unity capture efficiency. This work paves the way towards direct loading of laser cooled Helium into an optical dipole trap towards Bose-Einstein condensation.

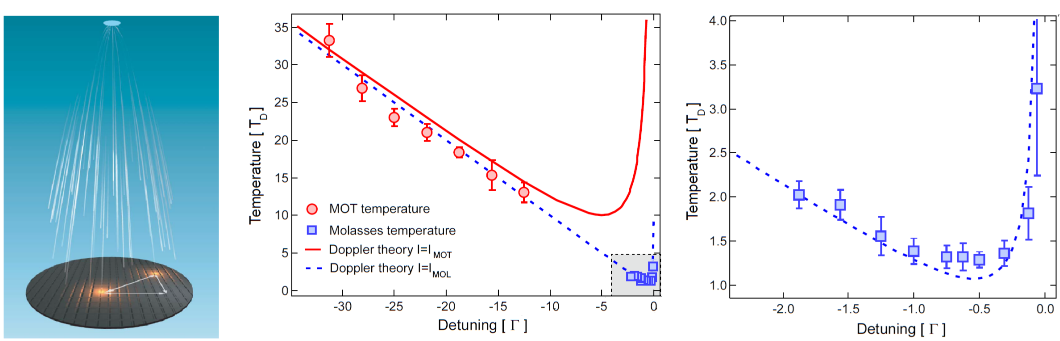

FIGURE 1. *Left* : Micro-channel plate detection of metastable Helium [1]. *Right* : Laser cooling in the purely Doppler regime. Measured temperature versus cooling laser detuning. Data (points) and Doppler theory (lines ; no adjustable parameters).

[1] T. Jeltes et al., "Comparison of the Hanbury Brown-Twiss effect for bosons and fermions", Nature **445**, 402-405 (2007).
[2] E. Toth et al., "Theory of correlations between ultracold bosons released from an optical lattice", Phys. Rev. A **78**, 013627 (2008).
[3] R. Chang et al., "Three-dimensional laser cooling of an atomc gas at the Doppler limit", arXiv :1409.2519 (2014).
[4] V. G. Minogin, and O. T. Serimaa, "Resonant light pressure forces in a strong standing laser wave", Opt. Commun. **30**, 373-379 (1979).
[5] A. Aspect et al., "Cooling Atoms with Stimulated Emission", Phys. Rev. Lett. **57**, 1688 (1986).
[6] M. Weidemüller et al., "A novel scheme for efficient cooling below the photon recoil limit", Eur. Phys. Lett., **27** (2), 109-114 (1994).

Tighter bounds for entanglement detection in spin lattice

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The paradigmatic many-body system consisting of spins located on a two or three dimensional lattices can now be realized with the help of optically trapped cold atoms. Here we are interested in systems of high spins, like those obtained in experiments performed in Refs. [1, 2], where the dynamics of thousands of Cr atoms (spin $s = 3$) trapped in a three-dimensional lattice is under study. In this system, interaction among particles is due to a strong magnetic dipole-dipole potential, which mediates experimentally observed [2] spin exchange between different lattice sites. This interaction is expected to create entanglement which we would like to detect experimentally.

Contrary to the case of few-party systems, where measurements can be done over individual observables to test Bell type inequalities as an entanglement witness [3], it is a difficult task, or even impossible in some cases, to address thousands of parties individually and measure correlations. Detecting entanglement can nevertheless be achieved by using inequalities involving only collective and experimentally accessible observables that have been recently developed [4–6]. These generalized spin squeezing inequalities require only the measurement of first and second moments of collective spin observables. The violation of one of these inequalities for a given state is a sufficient but not necessary condition for the presence of entanglement in the system. In the system discussed above [1, 2], preliminary numerical results suggest that entanglement in that system cannot be detected by these inequalities. This fact undoubtedly motivates us to engineer new expressions where such correlations can manifest.

We then revisited the derivation of these entanglement witnesses imposing new general and experimentally verifiable hypothesis. Basically, we inspected three assumptions: the constancy of the magnetization since no spin relaxation was observed in the experiments, no population in the extremal states $m = 3, 2$ as is experimentally seen when atoms are initially produced in $m = -2$, and translational invariance symmetry. These constraints lead to new bounds for these entanglement witnesses, which are significantly tighter and easier to violate than the original ones. Using a simplified model and numerical calculations, we demonstrate that these new bounds become useful to discriminate some entangled states produced experimentally.

[1] A. de Paz, *et al.*, Phys. Rev. A **87**, 051609 (2013).
[2] A. de Paz, *et al.*, Phys. Rev. Lett. **111**, 185305 (2013).
[3] N. Brunner, *et al.*, Rev. Mod. Phys. **86**, 419 (2014).
[4] O. Guhne and G. Toth, Phys. Rep. **474**, 1 (2009).
[5] G. Vitagliano, *et al.*, Phys. Rev. Lett. **107**, 240502 (2011); G. Vitagliano, *et al.*, Phys. Rev. A **89**, 032307 (2014).
[6] M. Wiesniak, V. Vedral, and C. Brukner, New J. Phys. **7**, 258 (2005).

Cavity-enhanced two-photon interferences with remote quantum dots

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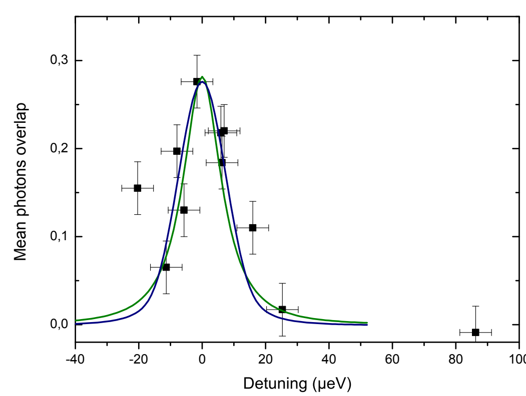
Indistinguishable single photons are at the heart of quantum communications. In this research area, using quantum interferences to implement efficient interactions between photons is crucial for teleportation of flying quantum states for example. Quantum dots (QDs) in microcavities are promising systems to implement solid state bright sources of single photons for quantum applications. Few years ago, quantum interferences between photons emitted by two distinct quantum dots have been demonstrated [1, 2]. More recently, ultrabright sources of indistinguishable single photon have been fabricated by coupling a QD to a microcavity [3]. An important step is now to demonstrate quantum interferences between two bright single photon sources.

To do so, we have deterministically fabricated two QD-pillars bright sources using the in-situ lithography technique [4], making sure that both pillar fundamental modes present the same energy. Each pillar embeds a single InGaAs QD (respectively QD1 and QD2) that are spectrally matched to their respective mode at 22.6 K and 19 K. At resonance, QD1 shows a Purcell factor of 14 resulting in a source brightness of 74% (i.e. 0.74 collected photons per pulse).

A Hong-Ou-Mandel experiment allows measuring the indistinguishability of successively emitted photons is characterized by a mean wavepacket overlap of M=77%. For QD2, the Purcell factor is 3 and the source indistinguishability hardly reaches M=12%. To interfere, photons emitted by QD1 and QD2 must have the same energy. To do so we keep unchanged the temperature of QD2 and tune the temperature of QD1 in a distant cryostat. When changing the temperature of the QD1 pillar, the exciton energy shifts. Consequently, the spectral detuning between QD1 and QD2 is changed. The measured mean wavepacket overlap reaches M=28% for zero detuning between the two sources. A direct consequence of the Purcell effect for both QDs, i.e. the acceleration of the emission in the mode, is a radiative broadening of the emission line (typically 1-3μeV for a QD without Purcell effect). Thanks to the radiative spectral broadening induced by the especially strong Purcell effect experienced by QD1, the spectral range of interference is the widest range (20μeV) ever measured to the best of our knowledge. We develop a simple theory to model the two-photon interference. Our theory takes into account the different dynamics of the sources, different decoherent mechanisms (solid lines) of emitted photons and the detuning in energy between the two QD lines.



Our results demonstrate that faster are the emitters, wider will be the spectral range for the interference. It paves the way to QD-based optical networks.

[1] R. Patel et al., "Two-photon interference of the emission from electrically tunable remote quantum dots", Nature Photonics **4**, 632 - 635 (2010) .

[2] E. Flagg et al., "Interference of single photons from two separate semiconductor quantum dots", Phys. Rev. Lett. **104**, 137401 (2010)

[3] O. Gazzano et al., "Bright solid-state sources of indistinguishable single photons", Nature Communications, **4**, 1425 (2013)

[4] A. Dousse et al., "Controlled Light-Matter Coupling for a single quantum dot embedded in a pillar microcavity using far-field optical lithography", Phys. Rev. Lett. **101**, 267404 (2008)

L. Lepori
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Title:
"Long-range interacting Kitaev chains"

Abstract:
I discuss a generalization of the Kitaev Ising chain with long-range paring term,
both with periodic and open boundary conditions.
The model is exactly solvable in terms of Bogoliubov excitations.
It is possible to identify a standard regime where the system behaves similarly to the usual Ising spin chain
and an exotic long-range regime where the correlation functions are power-law decaying
also in presence of a non vanishing mass gap,
the area law for the Von-Neumann entropy is violated
and the velocity of the excitations is diverging.
I also discuss the evolution of Majorana edge states decreasing the power-law exponent of of the pairing.
At the end I comment shortly on the effects by a long-range hopping term."

Fermi Golden Rule beyond the Zeno regime

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We investigate the spontaneous emission of light by an atomic dipole (two-level quantum system). The dipole is considered to be initially excited while all the electromagnetic field modes are taken to be, initially, in their vacuum (zero-photon) state.

In the standard treatment of this kind of problem, one derives the Fermi golden rule, which states that the probability that the dipole stays in its excited state (the so-called survival probability) decreases linearly with time. At longer times, the survival probability generally decreases exponentially. It is, on the other hand, well known that, under very general circumstances, the survival probability of a quantum system decays quadratically [1] -and not linearly- with time at very short times. This initial quadratic behaviour is known as the quantum Zeno regime.

We studied in detail the behaviour of an atomic dipole in the Zeno regime. Our calculations predict a small but sudden decrease of the survival probability, in conjunction with the emission of off-resonant light. For the $\mathrm{2p}-\mathrm{1s}$ transition in atomic hydrogen -within the rotating wave approximation- we found that electromagnetic modes with frequency up to a thousand times larger than that of the atomic transition are excited.

As we show, the transient Zeno regime is dominated by the collective, in phase, response of the electromagnetic field modes. Very quickly, this collective response gets out of phase (incoherent) so that non-resonant electromagnetic modes become, in a way, inactive. It is only at this point that the linear decay of the survival probability arises, as described by the Fermi golden rule. This linear decay is essentially driven by the resonant modes of the electromagnetic field.

In practice, it is difficult to excite an atomic dipole while making sure that all electromagnetic modes stay in their vacuum state. This might explain why our counterintuitive predictions have not been checked experimentally. This verification, however, is in principle not to be written off, but requires the taking into account of off-resonant modes into the experimental scheme.

[1] B. Misra and E.C.G. Sudarshan, "The Zeno's paradox in quantum theory", J. Math. Phys. **18**, 756 (1977).

Quantum cryptography over a full embryonic telecom network

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Quantum Key distribution (QKD) enables two parties, Alice and Bob, to share a sequence of random bit whose secrecy is guaranteed by the fondations of quantum physics. The natural counterpart of this genuine inviolability lies in moderate key generation rates and achievable distances, due to severe experimental constraints, such as photon generation probabilities, detector's inefficiencies, detector's dark counts, and losses in fiber distribution channels. As well as improving these experimental resources since the last couple of years, several strategies are developed for increasing this bit rate. One promising way consists in exploiting the spectral correlations of time-energy entangled photons, enabling higher information content per paired photon. Our idea is to combine the maturity of QKD schemes with high performance standard telecom components to propose a practical scheme allowing the distribution of secret bits over 200 km at unprecedented rates.

We report a scheme for quantum key distribution combining a high quality entangled photons-pair source (EPPS) based on spontaneous parametric down-conversion (SPDC), and off-the-shelf dense-wavelength-division-multiplexing (DWDM). This permits augmenting either the bit rate in a two-party scheme, or the number of users at constant rate [1–3]. Numerous QKD experiments have been built using a narrow spectrum with a 100 GHz filtering stage [4]. Here, we have opted for another approach, where we take advantage of the whole spectrum of our SPDC source (4 THz) [5]. In other words, one can exploit higher dimensionality available in a large spectrum of emission to improve the number of bits carried per paired photons. We chose to implement two 8 channels DWDM (see Figure 1) positioned symmetrically apart from the degenerate emission wavelength to serve as a proof of principle for the increase potential in terms key rate exchange.

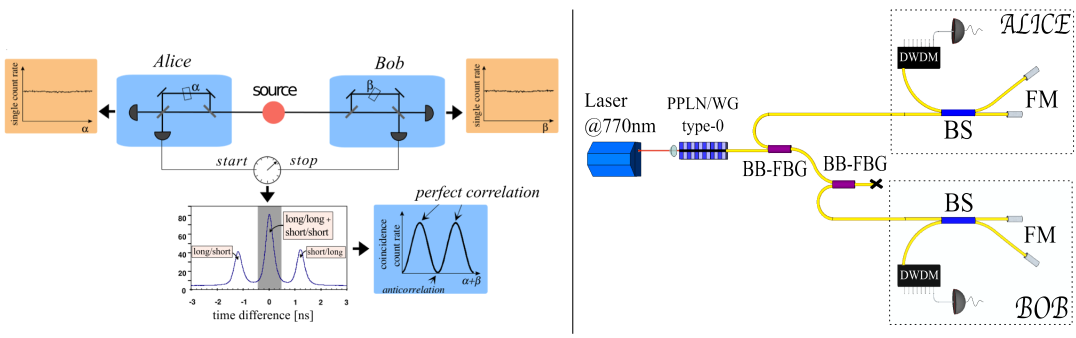

Figure 1 : (a) Phase coding protocol without DWDM. (b) Experiment : Broad Band Bragg Grating Filter (BB-FBG), Beam Splitter (BS), Faraday Mirror (FM)

We are then able to either distribute correlated photon pairs to 8 different couples of users with a single source, or to send the 8 outputs to a unique couple of users. Namely in the latter case, this would permit augmenting the bit rate exchange by a factor 8.

In this talk, we will first discuss the idea of DWDM-QKD, then describe the setup we have built for distributing energy-time entangled photon pairs over 200 km in standard telecom channels, and finally discuss the results we have obtained so far.

[1] J. Mower *et al.*, Phys. Rev. A **87**, 062322 (2013).
[2] J. Nunn *et al.*, Opt. Express **21**, 15959-15973 (2013).
[3] H. Lim *et al.*, Opt. Express **16**, 16052-16057 (2008).
[4] G. Ribordy *et al.*, Phys. Rev. A **63**, 012309 (2000).
[5] F. Kaiser *et al.*, Laser Phys. Lett. **10**, 045202 (2013).

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Quantum dynamics of an electromagnetic mode that cannot have N photons

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Electromagnetic modes are instrumental for realizing quantum physics experiments and building quantum machines. Their manipulation usually involves the tailoring of their Hamiltonian in time. An alternative control scheme, called Quantum Zeno Dynamics (QZD), consists in restricting the evolution of a mode to a subset of possible states [1]. This promising control scheme has been implemented earlier this year on atomic levels of Rb [2] and of a Rydberg atom [3]. In this talk, I will report the first observation of QZD of light, using superconducting circuits. By preventing the access to a single energy level, the dynamics of the field is dramatically changed [4]. Here, it was possible to avoid a number of photons N, which was arbitrarily chosen between 2 and 5. Under this constraint, and starting in its ground state, a resonantly driven mode is confined to levels 0 to N-1. The level occupation is then found to oscillate in time, similarly to an N-level system. Performing a direct Wigner tomography of the field reveals its non-classical features. In particular, at half period in the evolution, it resembles a "Schrödinger cat state". All these observations are well captured by a model based on N levels only. Our results demonstrate that QZD allows the direct control of the field state in its phase space. This experiment paves the way to the realization of various protocols, such as phase space tweezers [4], generation and protection of entanglement, and quantum logic operations.

[1] P. Facchi et al. Phys. Lett. A 275, 12-19 (2000) Phys. Rev. Lett. 89, 080401 (2002).
[2] F. Schäfer et al. Nat. Commun. 5, 3194 (2014).
[3] A. Signoles et al. arXiv : 1402.0111 (2014)
[4] J. M. Raimond et al. Phys. Rev. Lett. 105, 213601 (2010).

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Storage of up-converted telecom photons in a doped crystal

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Quantum memories provide an interface between stationary quantum bits (encoded in atom-like systems) and flying qubits (encoded in photons). They are for example useful for the implementation of ultra-long distance quantum communication using quantum repeater architectures [1]. Their integration into a fibre-based quantum network [2] requires optical interfaces between quantum memories and the telecom-wavelengths in order to minimize absorption. Our approach is the use of quantum frequency conversion [3] in a non-linear waveguide [4]. We report on an experiment that demonstrates the frequency up-conversion of telecommunication wavelength single-photon-level pulses to be resonant with a solid-state optical memory based on a $\mathrm{Pr}^{3+}:\mathrm{Y_2SiO_5}$ crystal [5]. We convert the telecom photons at $1570\,\mathrm{nm}$ to $606\,\mathrm{nm}$ using a periodically-poled potassium titanyl phosphate nonlinear waveguide. The maximum device efficiency (including all optical losses) is inferred to be $\eta_{\mathrm{dev}}^{\mathrm{max}} = 22\pm1\,\%$ (75 % internal efficiency) with a signal to noise ratio exceeding 1 for single-photon-level pulses with durations of up to $560\,\mathrm{ns}$. The converted light is then stored in the crystal using the atomic frequency comb scheme with storage and retrieval efficiencies exceeding $\eta_{\mathrm{AFC}} = 20\,\%$ for predetermined storage times of up to $5\,\mu\mathrm{s}$. The retrieved light is time delayed from the noisy conversion process allowing us to measure a signal to noise ratio exceeding 100 with telecom single-photon-level inputs. These results represent the first demonstration of single-photon-level optical storage interfaced with frequency up-conversion.

[1] N. Sangouard, C. Simon, H. de Riedmatten, and N. Gisin. *Rev. Mod. Phys.* **83** 33âĂŞ80 (2011).
[2] H. J. Kimble, *Nature* **453** 1023-1030 (2008).
[3] J. Huang and P. Kumar, *Phys. Rev. Lett.* **68** 2153 (1992).
[4] S. Tanzilli, W. Tittel, M. Halder, O. Alibart, P. Baldi, N. Gisin and H. Zbinden, *Nature* **437** 7055 (2005).
[5] N. Maring, K. Kutluer, J. Cohen, M. Cristiani, M. Mazzera, P. M. Ledingham, H. de Riedmatten, *New J. Phys.* Accepted (2014).

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Temporal shaping of single photon pulses

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The ability to control the temporal shape of single photon pulses is highly desirable in quantum information processing. For instance, it has been shown that Gaussian pulses are best suited for linear optics quantum computing [?]. By mimicking the time reversal of a spontaneous emission, it also allows to optimize the absorption of the prepared photons by a quantum emitter. In this work we investigate the potential of using fast modif cations of the detuning between an atomic system and a cavity during photon emission to reach this goal. We compare two approaches consisting of varying the atomic or cavity frequency. The latter, achievable by a fast modif cation of the refractive index of a solid state cavity, will be shown to have negligible inf uence on the photon spectrum. It allows to create gaussian pulses interacting with target photons with a visibility of 99% (Fig. 1.a)), as well as time reversed photons absorbed by an atom in a cavity with a probability of 93% (Fig. 1.b)).

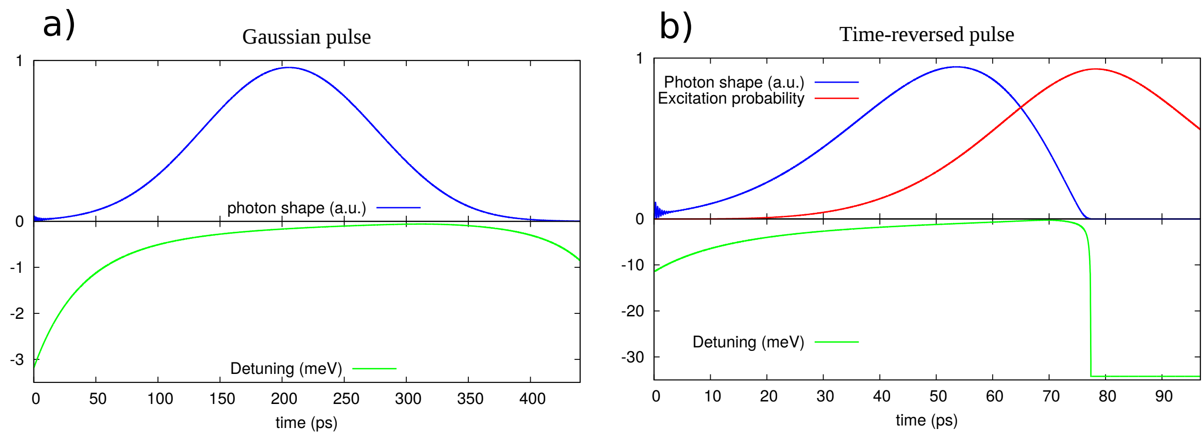

FIGURE 1. a) Temporal shape of a prepared gaussian pulse (top) and the corresponding detuning (bottom). The cavity has a quality factor of 5000 and a Purcell factor of 40 b) Temporal shape of a prepared time-reversed pulse (top, blue) and the corresponding detuning (bottom). The red curve is the atom's excitation probability where the time reference t=0 is the moment at which the pulse reach the receiving cavity. The emitting cavity has a quality factor of 1000 and a Purcell factor of 250. The receiving cavity has a quality factor of 15000 and a Purcell factor of 80.

[1] Peter P. Rohde, Timothy C. Ralph and Michael A. Nielsen, "Optimal photons for quantum-information processing" Phys. Rev. A 72, 052332 (2005).

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Electrical Control of Nuclear Spin Coherence of Rare-Earth Ions in Solids

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Nuclear spin levels of rare-earth ions in solids are very attractive candidates for q-bits in quantum memories and other quantum information applications because of their long coherence times T_2. Using nuclear spins in open shell ions with narrow optical resonances, such as rare earths (RE), introduces the possibility of using sensitive optical detection schemes to measure nuclear spin coherence and also of transferring coherence between nuclear and electronic states. The importance of RE doped crystals for quantum information processing is shown for example by the recent demonstration of a photon to crystal quantum state teleportation [1]. Moreover, it has been found that the coherence times of nuclear spin states can be greatly extended by the application of specific external magnetic fields or the application of specific rf pulse sequences [2, 3]. We show here that it is also possible to exercise control over the coherence properties of RE nuclear spins with electric fields (Stark effect). A combination of electric field induced spin- echo modulation and optical Raman heterodyne detection was used to measure the Stark effect of the nuclear quadrupole levels of dilute Eu^{3+} ions in Y_2SiO_5 with high sensitivity using electric fields of only $\approx$10 V/cm. To the best of our knowledge this is the first observation of the Stark effect on nuclear levels of RE ions, and the first application of optical techniques to the measurement of the Stark effect of nuclear states [4].

[1] F. Bussières, C. Clausen, A. Tiranov, B. Korzh, V. B. Verma, S. W. Nam, F. Marsili, A. Ferrier, P. Goldner, H. Herrmann, C. Silberhorn, W. Sohler, M. Afzelius, and N. Gisin, Quantum teleportation from a telecom-wavelength photon to a solid-state quantum memory, Nat. Photonics, vol. 8, pp. 775 ?778, 2014.

[2] M. Lovrić, P. Glasenapp, D. Suter, B. Tumino, A. Ferrier, P. Goldner, M. Sabooni, L. Rippe, and S. Kröll, ?Hyperfine characterization and spin coherence lifetime extension in Pr3+ :La2(WO4)3, ? Phys. Rev. B, vol. 84, p. 104417, 2011.

[3] M. Lovrić, D. Suter, A. Ferrier, and P. Goldner, Faithful Solid State Optical Memory with Dynamically Decoupled Spin Wave Storage, Phys. Rev. Lett., vol. 111, p. 020503, 2013.

[4] R. M. Macfarlane, A. Arcangeli, A. Ferrier, and P. Goldner, Optical Measurement of the Effect of Electric Fields on the Nuclear Spin Coherence of Rare-Earth Ions in Solids, Phys. Rev. Lett., vol. 113, p. 157603, 2014.

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Nano-optomechanical measurement with a single photon source

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We investigate a hybrid nanomechanical system in the form of a nanowire hybridized to a single NV defect attached to its extremity (Fig. a and b). The mechanical vibrations of the nanoresonator grant a spatial degree of freedom to the single quantum emitter and the photon emission event can now vary in space and time [1]. Furthermore, the photon detection is modulated as the source travels through the detection volume. We investigate how the nanomotion is encoded on the detected photon statistics and explore their autocorrelation properties in space and time. The simulation of arbitrary trajectories, such as Brownian motion of any temperature (Fig. c), is achieved through electrostatic actuation. A photon bunching of motional origin can be observed when the spatial spreading of the Brownian motion exceeds the optical resolution of the apparatus (Fig. d and e). Measuring the correlations from different locations, like in the original Hanbury Brown and Twiss experiment, permits to establish the space-time diffusion map of the single photon source. Furthermore, the analysis of the photon statistics allows to record the nanomechanical oscillator displacement noise at unprecedentedly low light intensities (typ. light power $\simeq 1\,\mathrm{fW}$), in the photon counting regime [2] (Fig. f and g). These developments can be transfered to weakly coupled nanomechanical oscillators such as nanotubes, or to experiments where very limited optical powers can be employed, such as in cryogenic environments.

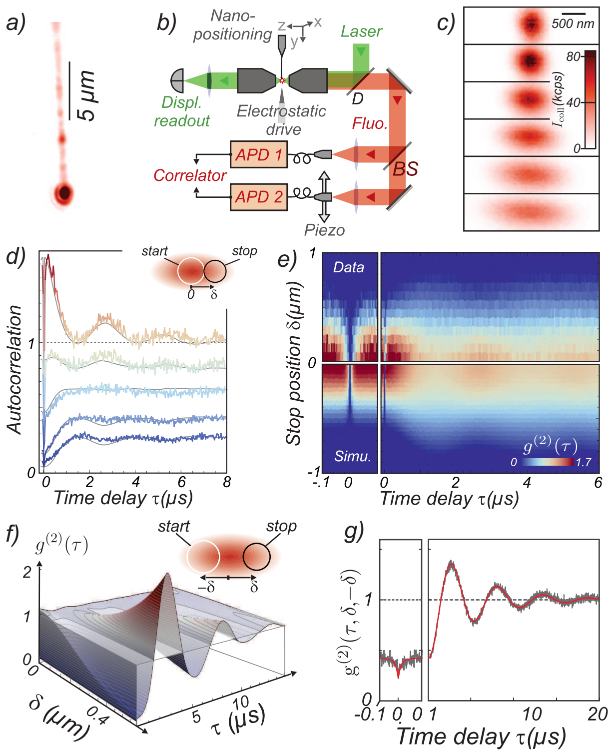

FIG. 1: a. Fluorescence image of a unique NV center attached to the tip of a nanowire. b. Schematic view of the setup. c. Integrated fluorescence of the single photon source in Brownian motion at different temperatures. d. and e. Fluorescence autocorrelation function for different temperatures and detection volume centerings. f. and g. Analytical development and experimental example of the vibration measurement.

[1] O. Arcizet, V. Jacques, A. Siria, P. Poncharal, P. Vincent and S. Seidelin, *"A single nitrogen-vacancy defect coupled to a nanomechanical oscillator"*, Nature Physics, **7**, 879883 (2011)
[2] L. Mercier de Lépinay, B. Pigeau, S. Rohr, A. Gloppe, E. Dupont-Ferrier, P. Verlot and O. Arcizet, *in preparation.*

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The Qubit in de Broglie-Bohm Interpretation

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In quantum information, the spin-based qubit is not represented by a whole spinor **in space** as illustred by the z spinor below :

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

but by a simplified spinor **without spatial extension** :

$$\Psi^0 = \begin{pmatrix} \cos\frac{\theta_0}{2} e^{-i\frac{\varphi_0}{2}} \\ \sin\frac{\theta_0}{2} e^{i\frac{\varphi_0}{2}} \end{pmatrix}.$$

This simplification is the basis of our first remark about the quantum computer concept. Indeed, the demonstrations explaining the interest of the Deutsch, Glover and Shor algorithms are based on calculations using the factorization of entangled qubits. These factorizations are accurate for spinors without spatial extensions, but only approximate for real spinors with spatial extensions.

A more fundamental remark concerns the existence of the qubit as a superposition of quantum states. This reality depends on the quantum mechanics interpretation. In the de Broglie-Bohm interpretation, the wave function (spinor) is not sufficient to completely describe the quantum state of a particle ; it is necessary to add the position of the particle. The spinor spatial extension takes into account the initial position of the particle. However, this position is unknown to the experimenter and is revealed only when measuring. Several particles prepared in the same way have the same wave function (spinor) but different positions. In this interpretation, the superposition of states does not really exist for an individual particle. It is only a linear combination of states resulting from our ignorance of the position of the particle. The superposition of states represents only a statistical collection of particles and the spinor corresponds to a statistical qubit.

We present a detailed study of the whole spinor evolution (in space and in time) in the Stern and Gerlach experiment and we explain the decoherence, the individual impacts and the quantization.

Our analysis explains very simply, in the de Broglie-Bohm interpretation, the negative results of the NMR technique in attempts to make a large quantum computer (more than 7 qubits). This technique does not use individual quantum objects, but a set of more than 10^8 active molecules diluted in a solvent : the measurement is thus a collective and reliable signal. The results of the NMR data being statistical, then we have a natural explanation of the drop by a factor two of the signal strength.

Finally, the parallel quantum computer is feasible in the interpretation of Deutsch and the parallel universes of Hug Everett, but impossible in the de Broglie-Bohm interpretation. In this interpretation, the individual qubit does not exist and we must use two particles to represent it ; the statistical qubit alone exists, such as in Chuang's computer.

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Hybrid quantum optomechanics : a single spin coupled to a nanomechanical oscillator

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Hybridizing a mechanical oscillator coupled to a purely quantum object permits investigating the quantum to macroscopic world interface and is a unique route toward the creation of counter intuitive non classical state of motion. On the way towards the quantum regime, emblematic signatures analog to the ones observed in the early age of quantum electrodynamics, such as Mollow triplet, are expected to arise from the hybrid coupling [1]. In our experiment, we investigate the coherent dynamics of a single spin qubit- of a NV defect in diamond- attached to the vibrating extremity of a SiC nanowire evolving in a strong magnetic field gradient. The later couples the spin state dynamics to the position of the nanomechanical oscillator, through the Zeeman effect. The Sic nanowire present intrinsically large oscillation amplitudes at high frequency and exhibit two orthogonally polarized fundamental modes. As a consequence of their ultra low masses they are very accurate vectorial force sensor. The NV center contains a single electronic (S=1) spin that can be manipulated and readout using optical and MW fields and present ultralong coherence times, which allows entering the resolved sideband regime of the hybrid interaction.

Similarly to a Stern-Gerlach experiment, the Zeeman energy of the spin is coupled to the oscillator position using a strong magnetic field gradient. Given the frequency difference between the oscillator (MHZ) and the two-level system (GHz), we concentrate on the parametric interaction regime, where the spin energy is modulated at the mechanical frequency by the nanomotion. This system [2] has the potential to enter the strong coupling regime. Moreover the parametric interaction can be turned resonant using a microwave dressing of the NV spin qubit. In the dressed basis, the Rabi frequency of the spin population can be tuned close the mechanical frequency. In this basis, the roles of the σ_z and σ_x operator are inverted and the interaction becomes resonant. As a result of this QED like Jaynes-Cummings interaction a phonon-dressed Mollow triplet was observed in the Rabi precession spectrum of the spin.

The experimental setup will be detailed and we will insist on the necessity to carefully control the alignment of static magnetic fields, microwave field, NV spin and vibration orientations. We will present the method developped to establish the cartography of the vectorial hybrid coupling strength in the vibration plane. The parametric interaction is then turned resonant by applying a microwave tone at the spin frequency whose strength is adjusted to match the Rabi precession and mechanical frequencies. This permits observing the synchronization of the spin dynamics onto the mechanical motion, which can also be directly interpreted as a phononic Mollow triplet in the hybrid spin-mechanical system. Moreover we will present how the 2D vectorial nature of the nanoresonator motion is imprinted onto the Mollow triplet signatures. We will also investigate the parametric quadratic coupling which was observed in regions of strong magnetic field gradients.

Finally we will discuss the perspectives upon the mechanical measurement of the single spin backaction, especially in the Mollow triplet regime where the synchronization of the spin dyanmics onto the mechanical motion provides new detection strategies.

[1] S. Rohr, E. Dupont-Ferrier, B. Pigeau, P. Verlot, V. Jacques, and O. Arcizet, "Synchronizing the Dynamics of a Single Nitrogen Vacancy Spin Qubit on a Parametrically Coupled Radio-Frequency Field through Microwave Dressing", PRL **112**, 010502 (2011).
[2] O. Arcizet, V. Jacques, A. Siria, P. Poncharal, P. Vincent and S. Seidelin, "A single nitrogen-vacancy defect coupled to a nanomechanical oscillator", Nature Physics **7**, 879 (2011)

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Localization loop spectroscopy for cold atoms in random potentials

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In phase-coherent systems, strong scattering by quenched disordered can suppress the real-space diffusion of matter waves, a phenomenon known as Anderson localization. While difficult to realize with interacting electrons, Anderson localization and its precursor, weak localization or coherent back-scattering, are today much studied with ultracold atoms in laser speckle potentials. We propose a conceptually new framework to study the dynamical onset of Anderson localization in disordered systems [1]. The idea is to expose the matter waves propagating in a random scattering potential to a sequence of short dephasing pulses. The system responds through coherence peaks forming at specific echo times, each echo representing a particular process of quantum interference. We suggest a concrete realization for cold gases, where quantum interferences can be observed in the momentum distribution of matter waves in a laser speckle potential, both in the backward [2, 3] and forward direction [4, 5].

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[1] T. Micklitz, C.A. Müller, A. Altland, arXiv:1406.6915.
[2] N. Cherroret, T. Karpiuk, C.A. Müller, B. Grémaud, C. Miniatura, Phys. Rev. A (R)**85**, 011604 (2012).
[3] F. Jendrzejewski, K. Müller, J. Richard, A. Date, T. Plisson, P. Bouyer, A. Aspect, V. Josse, Phys. Rev. Lett. **109**, 195302 (2012).
[4] T. Karpiuk, N. Cherroret, K. L. Lee, B. Grémaud, C. A. Müller, C. Miniatura, Phys. Rev. Lett. **109**, 190601 (2012).
[5] T. Micklitz, C.A. Müller, A. Altland, Phys. Rev. Lett. **112**, 110602 (2014).

Measurement of the Wigner Distribution Function of a leviton

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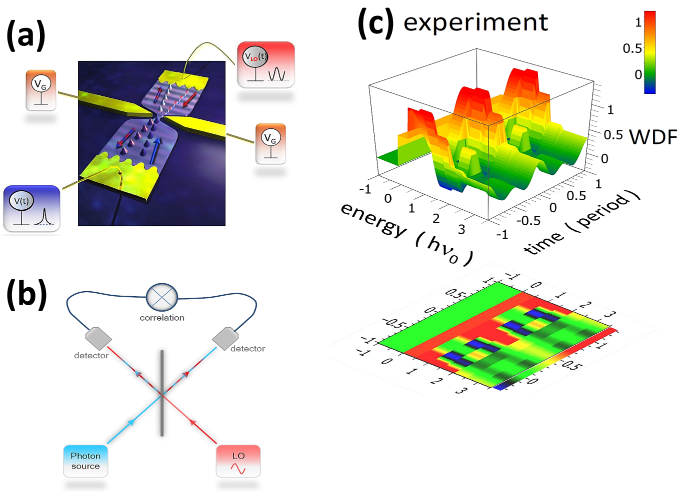
While standard quantum tomography for photons is obtained by mixing the unknown state with a large amplitude coherent photon field, for fermions like electrons in condensed matter this approach is not applicable as by nature a fermionic field is limited to small amplitude (at most one particle per state). To date no determination of an electron wave-function has been done. Recent proposals addressing quantum conductors suggest measuring the time dependent current of electronic wave interferometers[1] or the current noise of electronic Hanbury-Brown Twiss interferometers[2–4]. Here, despite the extreme noise sensitivity required, we show that such measurements are possible [5] and present the reconstructed wave-function quasi-probability, called Wigner Distribution Function (WDF), of single-electrons injected in a ballistic conductor. Many identical electrons are prepared in a well-controlled quantum state called leviton[6] by repeatedly applying Lorentzian voltage pulses on a contact. Sent to an electron beam-splitter, they are mixed with a weak amplitude fermionic field formed by a coherent superposition of electron-hole pairs generated by a small a.c. current of frequency multiple of the repetition frequency following the protocol proposed in Ref.[3]. Their anti-bunching with levitons at the beam-splitter changes the leviton partition statistics and the noise variations provide the energy density matrix elements of the levitons. The demonstration of quantum tomography makes the recent field of electron quantum optics with ballistic conductors a new test-bed for quantum information with fermions. These results may find direct application to probe entanglement of electron flying qubits, electron decoherence and electron interactions. They could be equally transposed to cold atoms made of fermions.



[1] Haack, G., Moskalets, M., and Büttiker, M., Glauber coherence of single-electron sources, Phys. Rev. B 87, 201302(R) (2013)
[2] Samuelsson, P. & Büttiker, M., Quantum sate tomography with quantum shot noise. Phys. Rev. B 73, 041305(R) (2006)
[3] Grenier, C. et al. Single-electron quantum tomography in quantum Hall edge channels, New Journal of Physics 13, 093007 (2011)
[4] Ferraro, D. et al. Wigner function approach to single electron coherence in quantum Hall edge channels, Phys. Rev. B 88, 205303 (2013)
[5] Jullien, T., Roulleau, R., Roche, B., Cavanna, A., Jin, Y., and Glattli, D. C., Nature doi :10.1038/Nature13821 (2014), in press.
[6] Dubois, J., Jullien, T., portier, F., Roche, P., Cavanna, A., Jin, Y., Wegscheider, W. and Glattli, D. C., Nature 502, 659-663 (2013)

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Multipartite entanglement in quantum hypergraph states

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This work focuses on the study of multipartite entanglement on a class of quantum states called hypergraph states [1], which are employed in many important quantum algorithms, such as Deutsch-Jozsa's and Grover's algorithms. These states are constructed according to mathematical objects called hypergraphs, and they are a generalization of well-known graph states [2]. With respect to graph states, for which there exists a wide literature, hypergraph states have been shown to have a much richer entanglement structure [3].

In this work we calculate a lower bound for multipartite entanglement in quantum hypergraph states. In particular we show a meaningful connection between the lower bound and the order of the maximal hyperedge appearing in the hypergraph. Our result states that the lower bound decreases when hyperedges of higher order are present. This counterintuitively suggests that an increase in the hypergraph complexity (i.e. the appearance of hyperedges of higher order) does not usually correspond to an increase of the entanglement content.

This result could be used to define witness operators able to detect entanglement within the class of these states. The aim would then be to produce optimal witnesses from an experimental perspective, namely witnesses which requires just a limited number of measurement settings, and thus are easy to be measured experimentally. These witnesses should also be tested in terms of robustness respect to noise.

[1] M. Rossi, M. Huber, D. Bruß and C. Macchiavello, New J. Phys. **15**, 113022 (2013).

[2] M. Hein, W. Dür, J. Eisert, R. Raussendorf, M. Van den Nest and H. J. Briegel, in Proceedings of the International School of Physics Enrico Fermi on Quantum Computers, Algorithms and Chaos (2005).

[3] O. Gühne, M. Cuquet, F. E. S. Steinhoff, T. Moroder, M. Rossi, D. Bruß, B. Kraus and C. Macchiavello, arXiv/quant-ph/1404.6492v2 (2014).

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Optimal Persistent Currents for Interacting Bosons on a Ring with a Gauge Field

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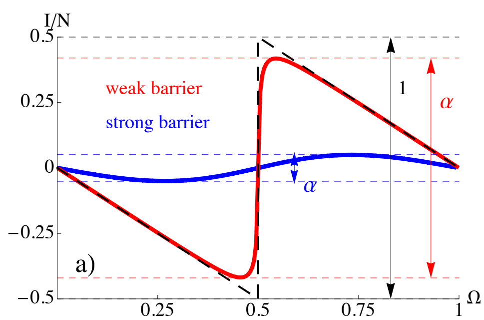
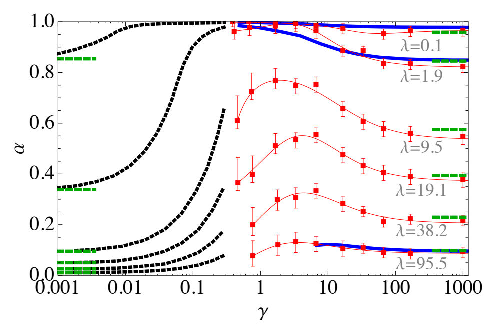
A quantum fluid confined on a ring and subjected to a $U(1)$ gauge potential displays a periodicity in the particle current as a function of the flux. This *persistent current* phenomenon is a manifestation of the Aharonov-Bohm effect, and reflects the macroscopic coherence of the many-body wavefunction along the ring. Recent developments in the manipulation of ultracold atoms on ring traps [1] have disclosed a novel platform for the study of persistent currents, which can be induced by the application of a rotating localized barrier, using well-focused laser beams. The unprecedented variety of interaction and barrier strength regimes paves the way to applications as atom interferometry and quantum information, *e.g.*, realizing a macroscopic superposition of current states and flux qubits [2].

In absence of any obstacle along the ring, the persistent currents display an ideal sawtooth behavior as a function of the flux for any interaction strength at zero temperature, corresponding to flowing states of well defined circulation. If a localized barrier is added, a superposition of different flowing states is produced, and the persistent currents are smeared, with a crossover to a sinusoidal form in the large-barrier limit (Fig. a).

The aim of our work is to provide a complete characterization of persistent currents for one-dimensional (1D) bosons, in all interaction and barrier strength regimes [3]. By combining analytical as well as numerical techniques, we show that the current amplitude is a nonmonotonic function of the interaction strength, which displays a pronounced maximum at intermediate interaction strength in all the regimes of barrier height (Fig. b). The presence of such an optimal regime for the current illustrates the highly non-trivial combination of correlations, quantum fluctuations and barrier effects. Our predictions are readily amenable to experimental testing with quasi-1D ultracold atomic gases confined in mesoscopic rings.



(a) Persistent current as a function of the flux Ω, in the first rotational Brillouin zone, for zero barrier (black dashed line), weak barrier (red line) and strong barrier (blue line), at fixed interaction strength.



(b) Persistent current amplitude α, as a function of the interaction strength γ at varying barrier strength λ, from Gross-Pitaevskii equation (black dotted lines), Luttinger liquid approach (blue solid lines), numerical DMRG calculations (red squares) and non-interacting and Tonks-Girardeau exact solutions (green dashes).

[1] K. C. Wright, R. B. Blakestad, C. J. Lobb, W. D. Phillips, and G. K. Campbell, Phys. Rev. Lett. **110**, 025302 (2013).
[2] D. W. Hallwood, T. Ernst, and J. Brand, Phys. Rev. A **82**, 063623 (2010).
[3] M. Cominotti, D. Rossini, M. Rizzi, F. Hekking and A. Minguzzi, Phys. Rev. Lett. **113**, 025301 (2014).

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Measuring two-electron wave-function in quantum Hall edge channels

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Probing quantum correlations within coherent conductors requires performing a two particle detection. In the framework of quantum optics, two photon detections are related to the second order coherence introduced by Glauber. On this poster, we introduce a second order electron coherence in the same spirit but in the context of electron quantum optics. We investigate the crucial role played by the Fermi sea in order to isolate the intrinsic contribution of an electron source. Then we focus on a few illustrative examples to enlighten the physical meaning of the intrinsic coherence of a source. Last, we propose an experimental scheme to access to quantum contribution to two-electron coherence through current correlation measurements performed in an Franson interferometer like setup.

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