TeQ#1

1st colloquium of the GdR TeQ "Quantum Technologies"

Université de Montpellier
Institut de Botanique
November 22-24 2023

https://gdrteqcolloq2023.sciencesconf.org/

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1 What is GdR TeQ ?

1.1 A CNRS "Research Network" on Quantum Technologies

The acronym **GdR TeQ** stands for "**Groupement de Recherche Technologies Quantiques**". It is a research network supported by the Centre National de la Recherche Scientifique (CNRS[1] GDR n°2149) through the (CNRS Physics[2]) and (CNRS Engineering[3]).

The goal of the GdR TeQ is to bring together the French community whose research activities fall within the broad spectrum of quantum technologies, ranging from physics to computer science, mathematics or chemistry. The GDR TeQ encompasses all the different types of physical support for quantum information, such as photons, trapped atoms and ions, quantum dots and point defects at the solid state, superconducting circuits, hybrid quantum systems... In particular, its scientific perimeter combines theoretical and experimental developments, including both very exploratory aspects and engineering aspects on mature technologies.
The GdR TeQ network gathers more than 1000 researchers spread over ∼100 French laboratories.

GdR TeQ is organized along six research axes (ART[4]) that currently underlie the development of quantum technologies all around the world, in particular within the European Quantum Flagship project and the French Quantum Plan:

- Quantum Communication & Cryptography – Qcom,
- Quantum Sensing & Metrology – Qmet,
- Quantum Processing, Algorithms, & Computation – Qpac,
- Quantum Simulation – Qsim,
- Fundamental Quantum Aspects – Fqa,
- Transverse Engineering and Methods – Tem.

More details on these research axes are provided on the GdR TeQ webpage: `https://gdr-teq.cnrs.fr/`.

1.2 Scientific Committee of the GdR TeQ

Audrey Bienfait (CNRS, ENS Lyon),
Juliette Billy (LCAR Toulouse),
Cyril Branciard (CNRS, Institut Néel Grenoble),
Anaïs Dréau (CNRS, Laboratoire Charles Coulomb Montpellier),
Jean Etesse (CNRS, Institut de Physique de Nice),
Omar Fawzi (INRIA, LIP Lyon),
Michele Filippone (CEA Grenoble),
Hanna Le Jeannic (CNRS, LP2N Bordeaux),
Anthony Leverrier (INRIA Paris),
Damian Markham (CNRS, LIP6 Paris),
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Sylvain Ravets (CNRS, C2N Palaiseau),
Matias Urdampilleta (CNRS, Institut Néel Grenoble),
Jérémie Viennot (CNRS, Institut Néel Grenoble),
Christophe Vuillot (INRIA, LORIA),
Mattia Walschaers (CNRS, LKB Paris).

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

2 TeQ#1 Colloquium – Scientific Information

2.1 Welcome !

TeQ#1 is organized by the GdR TeQ Scientific Committee and by the Laboratoire Charles Coulomb[5] at the University of Montpellier[6].
Its main goal is to gather members of various communities involved in Quantum Technologies and to foster exchanges about the latest advances in the field. The colloquium will feature four types of presentations:

- 5 tutorial talks (50'+10' discussion), providing the participants with a clear and pedagogical perspective on significant recent advances in specific branches of fundamental and applied research in the field,
- 5 invited talks (25'+5' discussion) on results that struck the most the scientific committee during the past year;
- 17 contributed talks (25'+5' discussion), representative of the different themes of GdR TeQ and selected among the 84 contributions received by the scientific committee for their scientific quality and for their general interest;
- 67 contributed posters, presented during two poster sessions according to their theme.

You will find in this book the abstracts of all of these contributions.

We would like to express our warmest thanks to the CNRS, the University of Montpellier, the Laboratoire Charles Coulomb and all our sponsors for their support in enabling us to organize the TeQ#1 colloquium.

We wish all the 168 participants a fruitful colloquium.

On behalf of GdR TeQ's Scientific Committee,

The organizers:

AnaïsDréau (CNRS researcher, L2C, President of TeQ#1 & Director of GdR TeQ),
Christelle Eve (local organizing, L2C),

Isabelle Philip (CNRS researcher, L2C),
Aurore Finco (CNRS researcher, L2C),
Guillaume Cassabois (UM professor, L2C),
Pierre Valvin (CNRS research engineer, L2C)
Bernard Gil (CNRS researcher, L2C),
Alexei Ourjoumtsev (CNRS, Collège de France & Deputy Director of GdR TeQ),

[5] https://coulomb.umontpellier.fr/
[6] https://www.umontpellier.fr/

2.2 Program of the colloquium

TeQ#1 - 1st colloquium of the GdR Quantum Technologies

	Wednesday Nov. 22nd 2023	Thursday Nov. 23rd 2023	Friday Nov. 24th 2024
08:30	**Welcome session**	**Tutorial FQA - Géraldine Haack (Univ. Geneva, CH)** ***"Quantum thermal machines"***	
09:00	**Quantum GDR overview**		**Tutorial QPAC - Simone Gasparinetti (Univ. Chalmers, SE)** ***"Quantum computing with superconducting bosonic modes: states, gates, tomography"***
09:30	**Tutorial QSIM - Iacoppo Carusotto (Pitaevskii BEC Center, Trento, IT) *"Quantum fluids of light as quantum simulators for condensed matter and gravitational problem"***	FQA - Carlos Lopetegui (LKB, FR) *"Metrological witness for non-Gaussian quantum entanglement"*	
10:00		Coffee break	QPAC- Kyrylo Gerashchenko (LKB,FR) *"Towards quantum control of an ultracoherent mechanical resonator with a fluxonium qubit"*
10:30	Coffee break	**Invited talk FQA - Ludovico Lami (Univ. Amsterdam & QuSof, NL) *"On the (ir)reversibility of entanglement manipulation"***	Coffee break
11:00	**Invited talk QSIM - Jean-Philippe Brantut (EPFL, CH) *"Photon-induced density-wave order in strongly correlated matter"***	FQA - Valeria Vento (EPFL, CH) *"Measurement-induced collective vibrational quantum coherence under spontaneous Raman scattering in a liquid"*	QPAC-Hugo Perrin (KIT,DE) *"Mitigating crosstalk errors by randomized compiling: Simulation of the BCS model on a superconducting quantum computer"*
11:30	QSIM - Martin Guillot (C2N, FR) *"All-optical measurement of the eigenstate structure in polariton lattices"*	FQA - Adrien Bensemhoun (INPHYNI, FR) *"Multipartite entanglement in bright frequency combs out of microresonators"*	QPAC - Bruno Senjean (ICGM, FR) *"Quantum Density Functional Theory on Qudit-based device"*
12:00	QSIM - Nicolas Ombredane (LCAR, FR) *"Floquet operator engineering for quantum state stroboscopic stabilization"*	Lunch	**Invited talk TEM - Dafei Jin (Univ. ND,USA) *"Single electrons on solid neon – a long-coherence high-fidelity qubit platform"***
12:30	Lunch		Lunch
13:00			
13:30		**Tutorial QCOM - Val Zwiller (KTH, SE)** ***"Generation, manipulation and detection of single photons"***	
14:00	**Tutorial QMET - Sébastien Merlet 'LNE- SYRTE, FR) *"Cold atom gravimetry***		TEM - Fabio Pistolesi (LOMA, FR) *"Carbon Nanotube Oscillator as a Nanomechanical Qubit"*
14:30		QCOM - Manon Huguenot (Exail, LIP6, FR) *"Development of industrial continuous-variable quantum key distribution systems"*	TEM/QSIM - Romain Long (LKB, FR) *"From cavity-protected atomic ensemble to single atom array in a microcavity"*
15:00	QMET - Jaime Travesedo (SPEC, FR) *"Single electron-spin-resonance detection by microwave photon counting"*	Coffee break	TEM - Valentin Magro (JEIP, FR) *"Deterministic freely propagating photonic qubits with negative Wigner functions"*
15:30	Coffee break	**Invited talk QCOM - Constanza Toninelli (CNR-INO, LENS, IT)** ***"Single molecules in photonic quantum technologies"***	Closing session
16:00	**Invited talk QMET - Nicolas Roch (Institut Néel, FR) *"Josephson waveguide : near quantum-limited amplifiers and beyond"***	QCOM - Thomas Van Himbeeck (IP-Paris, FR) *"A tight and general finite-size security proof of quantum key distribution"*	
16:30	QMET - Eleonora Capocasa (APC, FR) *"Squeezed-vacuum techniques for quantum noise reduction in interferometric gravitational-wave detectors"*	QCOM - Louis Nicolas (Univ. Geneva, CH) *"Towards large bandwidth spin-wave AFC storage in 171Yb3+:Y2SiO5"*	
17:00	QMET - Nicolas Fabre (IP-Paris, FR) *"Time-frequency quantum metrology"*	Poster session 2 **QMET, FQA**	
17:30	Poster session 1 **QCOM, QPAC, TEM, QSIM**		
18:00		Banquet	
18:30			
19:00			
19:30			

3 TeQ#1 Colloquium – Practical Information

3.1 Venue

Oral sessions will take place in the amphitheater at:

Institut de Botanique
163 rue Auguste Broussonnet
34090 Montpellier.

Poster sessions will take place in the main hall, close to the entrance of the Institut Botanique. The maximal format for posters is A0, portrait orientation. Posters submitted to QCOM, QPAC, TEM and QSIM themes will be presented on Wednesday 22$^{\text{nd}}$ November 2023, 17:30-19:30. Posters submitted to QMET and FQA themes will be presented on Thursday 23$^{\text{rd}}$ November 2023, 17:00-18:00. Posters submitted to more than one theme will be presented during the second (Thursday) session.

Coffee breaks, lunches and the conference dinner will take place in the main hall.

The *Institut de Botanique* building, classified as a French Historic Monument, adjoins the Garden of Plants, the oldest botanical garden in France, founded by Henri IV in 1593. It is also located on the edge of the historical center of Montpellier "l'Ecusson".

(a) Institut de Botanique @Aurélia Held, Université de Montpellier.

(b) The Garden of Plantes @Université de Montpellier.

How to reach the Institut de Botanique by public transport

- **Arriving at Montpellier Saint Roch train station:**

  Exit the train station from the main entrance (towards the city center and Comédie place), take the tramway line 4 towards "Garcia Lorca" and get off at the stop "Albert 1er - Cathédrale". Alternatively, if you prefer to walk, the conference site is a 21-minute walk away from Montpellier Saint-Roch train station (see map 1).

- **Arriving at Montpellier Sud de France train station:**

  This train station is 6-km away from Montpellier city center. First, take the shuttle that will bring you to the tramway line 1, stop "Place de France". Then take the tramway line 1 towards "Mosson" and get off at the stop "Albert 1er".

- **Arriving at Montpellier Méditerranée airport:**

  Take the shuttle ligne 620 towards "Place de l'Europe", then take the line 1 towards "Mosson" and get off at the "Albert 1er" stop.

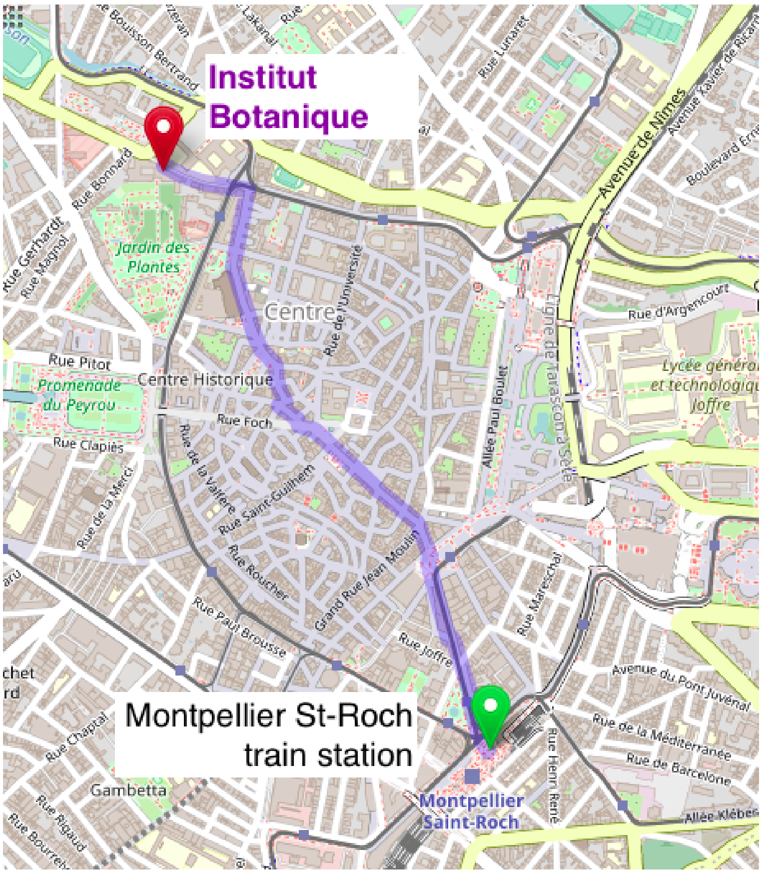

Figure 1: 21-minute walk path through the historical city center of Montpellier to reach the *Institut de Botanique* from Montpellier St Roch train station.

4 Host institution & sponsors of the colloquium

4.1 Parent institution

The Centre National de la Recherche Scientifique (CNRS) is an interdisciplinary public research organisation under the administrative supervision of the French Ministry of Higher Education, Research, and Innovation (MESRI). The CNRS chooses to pursue research excellence that explores natural and social phenomena in greater depth, in an effort to push back the frontiers of knowledge.

The research network "Quantum Technologies" (GdR TeQ) is linked to and supported by the CNRS Physics (formerly INP). CNRS Physics's research thematics relate to the fundamental laws of physics, understanding radiation, matter, and their interactions. Those studies come with two main motivations : understanding the world, and answering current societal challenges.

The GdR TeQ also benefits from secondary support from the CNRS Engineering (formerly INSIS).

4.2 Host institution

The University of Montpellier currently welcomes more than 51,000 students in its 17 faculties, schools and institutes. Located throughout the city of Montpellier and in the main cities of the eastern part of the Occitanie region, they cover the main fields of study: law, economics, management, political and social sciences, science, technology and health, thus enabling students to move towards professional careers and/or the world of research.
The University of Montpellier has 74 research facilities and 15 technology platforms spread over 5 research clusters: 1) agriculture, environment, biodiversity, 2) biology-health, 3) chemistry, 4) mathematics, computer science, physics and systems, 5) social sciences.

4.3 Sponsor

The Laboratoire Charles Coulomb (L2C) is a joint Research Unit (UMR 5221) between CNRS and University of Montpellier. The L2C covers a wide range of fields, from the most mathematical theoretical Physics to Chemical Physics and Biophysics, with a solid background of theoretical and experimental research devoted to Condensed Matter and Nanosciences. The investigations performed at the L2C are often at the interface with Chemistry, Life Sciences and Electronics. The L2C possesses an ensemble of high-level experimental techniques, in particular, a unique set of optical spectroscopy facilities. Mainly concerned with Basic Physics, the L2C is nevertheless at the center of numerous collaborations with industrial partners, and of applied research leading to the filing of several patents and to the creation of start-ups.

Welinq is a spin-off company from Sorbonne Université working on the interconnection of Quantum Processors. We develop full-stack quantum links relying on a high-performance quantum memory to share entanglement between remote quantum nodes. Our work paves the way to distributed quantum computing and long-distance links of the Quantum Internet.

THORLABS est leader dans la fabrication et la distribution de composants pour l'industrie et la recherche dans les domaines de l'optique et de la photonique. Nous proposons une large gamme de composants (+ de 20000 références) que nous concevons, fabriquons et distribuons. Notre présence est mondiale, avec des bureaux commerciaux, des usines de fabrication et des plateforme logistiques aux USA, Canada, Brésil, Japon, Chine, Allemagne, Royaume-Uni, Suède et en France.

Quandela is a french start up that provides photonic quantum computers that are modular, scalable, energy-efficient and accessible both on the cloud and on premise. Our team specialises in the development of both software and hardware solutions for a variety of quantum applications. We offer a wide range of services, from developing the most efficient and brightest single photons sources, to creating algorithms for quantum computers and providing cloud quantum computing solutions.

PASQAL is a spin-off from the Institut d'Optique at Palaiseau. The company now employs over 200 people, including a strong team of experts in atomic and optical physics, trained at leading quantum research institutes. PASQAL is developing large-scale quantum processing units (QPUs) based on neutral atoms, the most promising approach to building commercial-grade quantum computers

5 Abstracts, Participants and Authors

The following section contains the abstracts of the tutorial talks, the invited talks, the contributed talks, and all the posters sorted according to their session and theme. They are followed by the list of authors of the presented papers.

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Tutorials

Quantum fluids of light as quantum simulators for condensed matter and gravitational problem

Iacopo Carusotto[1]
[1]*Pitaevskii BEC Center, INO-CNR and Dipartimento di Fisica,*
Università di Trento, I-38123 Trento, Italy

After a short comparative summary of the main platforms for quantum simulation, I will focus on quantum fluids of light and on their potential for quantum simulations. I will consider both the driven-dissipative dynamics of quantum fluids of light in cavity devices and their unitary dynamics in propagating configurations. Recent highlights of this field of research will be reviewed, as well as its exciting perspectives for quantum simulation of major problems in condensed matter and gravitational physics, such as fractional quantum Hall physics and Hawking radiation from black holes.

Cold atom gravimetry

Sébastien Merlet[1]
[1]*LNE-SYRTE, Observatoire de Paris - Université PSL,*
CNRS, Sorbonne Université,
61 avenue de l'Observatoire 75014 Paris

Gravimetry is the science of the measurement of gravity acceleration g, which include its magnitude, gradient and direction. Applications mainly concern geophysics and several different classes of sensors are used. Since the 1990s and developments based on laser-cooled atomic sources, new sensors have been studied and developed, first in US, followed by Europe and now all over the world. Indeed, atom interferometry makes it possible to create new types of instruments for geophysics and, in particular, gravimetry. The tutorial will present and compare the instrumentation in this domain focusing on cold atom gravimeters. The operation principle of such sensors will be explained, taking as an example the LNE-SYRTE Cold Atom Gravimeter (CAG). The industrial transfer of this technology has already been completed and several companies now offer this type of instrument. The performances of the sensors will be detailed as well as their main limitations. To conclude the tutorial, the evolution of the domain, current perspectives and new projects will also be presented.

Quantum thermal machines

Géraldine Haack[1]
[1]*Department of Applied Physics, University of Geneva, Switzerland*

Quantum thermal machines can be seen as paradigmatic open quantum systems for understanding energy exchanges at the quantum scale, as well as the intimate connection between quantum thermodynamics and quantum information theory. In particular, one would like to determine whether quantum features, like entanglement, interactions and quantum statistics, can be beneficial to the efficiency of a thermal machine made of few quantum constituents. This research direction becomes even more fascinating in view of recent experimental progresses towards manipulating out-of-equilibrium multi-partite quantum systems, allowing for genuine quantum features. In this tutorial, I will introduce some of the main concepts and tools for approaching these questions and present a selection of our latest results concerning the advantages that open quantum systems can offer towards heat management at the nanoscale, including energy storage and dissipative-based quantum control.

Generation, manipulation and detection of single photons

Val Zwiller[1]
[1]*Quantum Nanophotonics, dept. of Applied Physics, Royal Institute of Technology, Stockholm, Sweden*

We develop quantum devices to enable the implementation of quantum technologies based on controlling light at the single photon level. Future quantum communication and sensing will require high-performance quantum devices able to generate and detect light one photon at a time. Schemes to manipulate light on-chip, based on integrated photonics are carried out in our group. Our single photon sources based on semiconductor quantum dots can generate single photons as well as entangled photon pairs at telecom wavelengths to enable implementation of long distance quantum communication. We operate a quantum network made of deployed optical fibers in the Stockholm area and demonstrate single photon transmission and quantum key generation over 34 km. Single photon detectors with high detection efficiency, low noise and high time resolution are major enabling techniques, our spinoff company Single Quantum develops superconducting nanowire single photon detectors with applications in quantum communication, integrated quantum circuits as well as for lidar and quantum microscopy. We will discuss these applications along with the specific detector requirements for technologies based on single photon detection. Further improvements in terms of time resolution, photon number resolution and extended detection ranges will also be discussed.

Quantum computing with superconducting bosonic modes : states, gates, tomography

Simone Gasparinetti[1]
[1]*Department of Microtechnology and Nanoscience,*
Chalmers University of Technology,
412 96 Gothenburg, Sweden

I will review our experimental efforts towards quantum computation with bosonic modes. Our platform consists of superconducting circuits with Josephson junctions coupled to microwave cavities and resonators. I will discuss two methods to prepare nonclassical states useful for computation. The first method utilizes a superconducting qubit as a nonlinear controller for the bosonic mode. The second method exploits built-in, microwave-activated nonlinearities in the bosonic mode. I will also report on the demonstration of quantum gates on a logical qubit encoded in the bosonic mode, and the full process tomography of these gates using coherent states as probes.

Invited talks

Photon-induced density-wave order in strongly correlated matter

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I will present the realization of a quantum degenerate Fermi gas interacting simultaneously via unitary-limited contact interaction and long-range, photon mediated interaction, induced by an optical cavity. We observe the onset of density-wave order above a critical strength of the photon-mediated interaction, and characterize the phase diagram as a function of both interactions type. Due to the interplay of light-matter interactions and pairing, a new type of optical resonance emerges, the pair-polariton, that provides means to synthesize photon-mediated three and four-body interactions. I will discuss the perspectives open by this new system and potential applications to cavity-based quantum simulators to other areas of physics.

Josephson waveguide : near quantum-limited amplifiers and beyond

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Josephson waveguides have recently emerged as very promising platform for superconducting quantum science and technologies. Their distinguishing potential resides in ability to engineer them at sub-wavelength scales, which allows complete control over wave dispersion and nonlinear interaction. In this talk I will discuss a Josephson waveguide with strong third order nonlinearity, which can be tuned from positive to negative values, and suppressed second order non-linearity. As first implementation of this versatile meta-material, we operate it to demonstrate a novel reversed Kerr phase-matching mechanism in traveling wave parametric amplification. In a second part, I will report on our recent observation of non-reciprocal amplification using the versatility of these Josephson waveguides. Besides such advances in amplification performance, Josephson meta-materials open up exciting experimental possibilities in the general framework of microwave quantum optics, single-photon detection and quantum-limited measurement.

On the (ir)reversibility of entanglement manipulation

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A long-standing open problem in quantum information is whether the theory of entanglement manipulation can be formulated as a thermodynamical theory. Such a formulation, colloquially known as a "second law of entanglement", would allow asymptotically reversible interconversion of pure and mixed entanglement — much like work and heat can be reversibly interconverted in classical thermodynamics — and would single out a unique entanglement measure that mirrors the role of entropy in thermodynamics. Contrary to previous promising evidence, here we show that a thermodynamical formulation of entanglement is impossible if the operations with which we manipulate this resource are required to be "non-entangling", i.e. such that they always map unentangled states to unentangled states. In this context, no direct counterpart to the second law of thermodynamics can be established. This is based on our recent work [1]. A glimmer of hope remains if one is willing to accept operations that can inject some amount of entanglement into the system. Whether reversibility can be restored in this way is a famous open problem known as the "Generalised Quantum Stein's Lemma", whose solution would have a range of implications much beyond entanglement manipulation. A proof of it was claimed long ago by Brandão and Plenio [2], but we recently found a serious flaw in that argument that substantially undermines it [3]. I will briefly touch upon the implications of these recent developments.

[1] Lami/Regula, Nat. Phys. 19 :184-189, 2023.
[2] Brandão/Plenio, Commun. Math. Phys. 295 :791, 2010.
[3] BBGLPRT, Quantum 7 :1103, 2023.

Single molecules in photonic quantum technologies

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The generation and manipulation of quantum states of light is required for key applications, such as photonic quantum simulation, linear optical quantum computing, quantum communication, and quantum metrology. In this context, single organic molecules in the family of polycyclic aromatic hydrocarbons (PAH), embedded in suitable host matrices, offer competitive properties and key advantages [1]. Being very small and with well-defined transition dipole moments, they can be used as nanoscopic sensors e.g. of pressure, strain, temperature, electric and magnetic fields, as well as optical fields. Furthermore, PAH molecules can be easily fabricated and exhibit strong zero-phonon lines, which reach their Fourier-limited natural linewidth at liquid helium temperature, thus providing very bright and stable sources of coherent photons in the solid state [2,3,4].
I will present our recent advances on the coupling of single PAH molecules to photonic structures for the enhancement and control of their interaction with quantum light [5,6]. Furthermore, I will discuss two-photon interference (TPI) experiments performed between single-photons emitted by distinct molecules on the same chip [7] (see Fig.1), which stands as a fundamental challenge in the context of solid-state platforms for photonic quantum techs.
In this context, we attain and combine together different milestones: simultaneously addressing on the same sample several molecules operating as on-demand single-photon sources, tuning independently their relative optical frequency [8], measuring in semi-real-time their TPI, and extracting information about joint properties of the photon pairs.
Finally, I will present our recent results on the use of organic molecules as nanoscopic thermal sensors [9], allowing semi-invasive local temperature measurement in a temperature range (3 K to 30 K) where most commercial technologies cannot be used. These results can lead to a deeper understanding of the local phononic environment in complex structures and in an unexplored temperature regime.

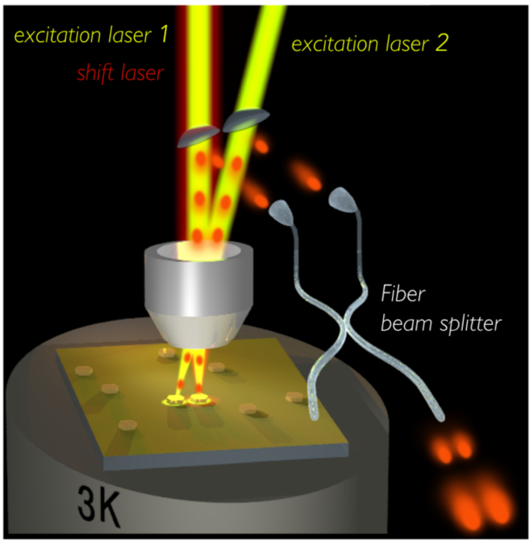

Figure 1: Sketch of the experimental setup employed to measure TPI from distinct molecules, adapted from Ref. [7]

References

[1] C. Toninelli et al., Nat. Mat. 20, (2021)
[2] S. Pazzagli et al., ACS Nano 12, (2018)
[3] P. Lombardi et al., Ad.Q.Tec. 3, (2020)
[4] P. Lombardi et al., Appl. Phys. Lett. 118, 204002 (2021)
[5] P. Lombardi et al., ACS Photonics 5, 126-132 (2018)
[6] M. Colautti et al., Ad.Q.Tech. 3, (2020)
[7] R. Duquennoy et al., Optica 9, 731-737, (2022)
[8] M. Colautti, et al., ACS Nano 14, 13584–13592 (2020)
[9] V. Esteso et al., Phys. Rev. X Quantum 4, 040314 (2023)

Single electrons on solid neon – a long-coherence high-fidelity qubit platform

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In this talk, I will present our discovery and development of a new qubit platform based upon isolated single electrons trapped on an ultraclean solid neon surface in a vacuum [1, 2]. Our electron-on-neon (eNe) charge (motional) qubits are controlled and readout by microwave photons in an on-chip superconducting resonator. The measured relaxation and coherence times have both reached the order of 0.1 ms, surpassing all existing charge qubits and rivalling state-of-the-art superconducting transmon qubits. Single-shot readout fidelity without a quantum-limited amplifier has reached 98.1%. Average single-qubit gate fidelity with Clifford-based randomized benchmarking has reached 99.97%. Utilizing a high-kinetic-inductance resonator, our latest results have shown much enhanced electron-photon coupling strength. This paves the way towards strong-dispersive coupling between two qubits and hence realization of two-qubit entangling gates for universal quantum computing.

[1] X. Zhou et al., "Single electrons on solid neon as a solid-state qubit platform", Nature 605, 46–50 (2022).

[2] X. Zhou et al., "Electron charge qubits with 0.1 millisecond coherence time", Nature Physics (2023).

Contributed talks

All-optical measurement of the eigenstate structure in polariton lattices

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In the field of topological photonics, exciton-polariton cavities have emerged as a promising platform, thanks to the complementary nature of their matter and light components. Indeed, the excitonic part provides large nonlinearities and susceptibility to magnetic fields, allowing time-reversal symmetry breaking, whereas the photonic part allows the engineering of gain, losses or the equivalent of spin-orbit coupling for photons. Thanks to all of this, exciton-polariton systems allow the study of a wide variety of phenomena, such as Chern insulators (1), quantum spin Hall effect (2), non-Hermitian skin effect (3), topological lasing (4) or topological gap solitons (5). Moreover, the open nature of exciton-polariton cavities makes them ideally suited to the measurement of geometrical and topological properties underlying these phenomena.

Here, we present a new experimental method to reconstruct the full eigenvector structure of a polariton lattice with an arbitrary number of degrees of freedom. We then use it to fully measure the geometrical properties of a polaritonic valley-Chern insulator, showing the difference in Berry curvature sign on both sides of an interface presenting edge states. We also report the experimental signature of the opening of a topological gap in a specially designed polariton honeycomb lattice showing large TE-TM and Zeeman splitting (6). We follow with our method the transition from a trivial phase to a Chern number $C = \pm 2$ topological phase through the polarization and sub-lattice localization properties of the eigenmodes of the system showing clear sign of band inversion.

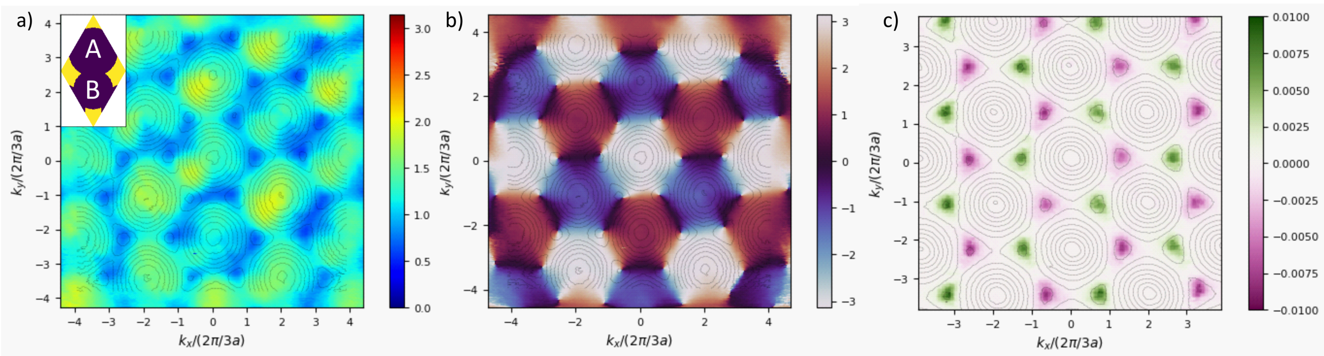

Figure 1: Bloch sphere representation $|\Phi\rangle = [cos(\theta)\exp^{i\phi}, sin(\theta)]$ in the $(|A\rangle, |B\rangle)$ basis of the upper band eigenvector structure for a honeycomb lattice with on-site energy. **a)** Co-latitude angle θ quantifying the degree of localization on either A or B sublattice (unit cell in inset), the dashed lines represent measured iso-energies of the dispersion. **b)** Azimutal angle ϕ representing the relative phase between both sublattices, clear vortexes can be seen in both K and K' valleys winding in opposite directions. **c)** Berry curvature of the band showing poles of opposite sign in both valleys, a feature characteristic of valley-Chern insulator.

References

1. S. Klembt et al., Nature **562**, Number: 7728 Publisher: Nature Publishing Group, 552–556, ISSN: 1476-4687, (2023; https://www.nature.com/articles/s41586-018-0601-5) (Oct. 2018).
2. C. Leyder et al., Nature Physics **3**, Number: 9 Publisher: Nature Publishing Group, 628–631, ISSN: 1745-2481, (2023; https://www.nature.com/articles/nphys676) (Sept. 2007).
3. From the Topological Spin-Hall Effect to the Non-Hermitian Skin Effect in an Elliptical Micropillar Chain (2023; https://pubs.acs.org/doi/pdf/10.1021/acsphotonics.1c01425).
4. P. St-Jean et al., Nature Photonics **11**, Number: 10 Publisher: Nature Publishing Group, 651–656, ISSN: 1749-4893, (2023; https://www.nature.com/articles/s41566-017-0006-2) (Oct. 2017).
5. N. Pernet et al., Nature Physics **18**, Number: 6 Publisher: Nature Publishing Group, 678–684, ISSN: 1745-2481, (2023; http://www.nature.com/articles/s41567-022-01599-8) (June 2022).
6. A. Nalitov, D. Solnyshkov, G. Malpuech, Physical Review Letters **114**, Publisher: American Physical Society, 116401, (2021; https://link.aps.org/doi/10.1103/PhysRevLett.114.116401) (Mar. 16, 2015).

Floquet operator engineering for quantum state stroboscopic stabilization

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Cold atoms constitute a highly controllable platform well suited for quantum simulations and quantum metrology. To this aim, quantum optimal control (QOC) is a valuable tool allowing preparation of a wide range of states that could not be produced using standard methods. In our system, a Bose-Einstein condensate (BEC) in a 1D optical lattice, QOC is used to optimize the time evolution of the lattice phase in order to prepare specific target states of the BEC collective wavefunction. We have recently demonstrated our ability to control and prepare states that are not eigenstates of the system such as arbitrary momentum states with chosen relative phases [1], superpositions of gaussian states and squeezed states in the phase-space of each lattice cell [2]. To certify the preparation of the chosen states, we reconstruct the final state using a maximum likelihood algorithm. I will also present experimental applications of QOC to realize a stroboscopic stabilization of quantum states of the BEC by exploiting space and time symmetries or by directly generating with QOC a stabilizing Floquet operator [3].

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[1] N. Dupont et al., *PRX QUANTUM*. **2**, 040303 (2021).
[2] N. Dupont et al., *New J. Phys.*. **25**, 013012 (2023).
[3] F. Arrouas et al. Floquet operator engineering for quantum state stroboscopic stabilization. 2023. arXiv : 2307.15476 [cond-mat.quant-gas].

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Single electron-spin-resonance detection by microwave photon counting

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Electron spin resonance (ESR) spectroscopy is the method of choice for characterizing paramagnetic impurities, with applications ranging from chemistry to quantum computing, but it gives only access to ensemble-averaged quantities due to its limited signal-to-noise ratio. The sensitivity needed to detect single electron spins has been reached so far using spin- dependent photoluminescence, transport measurements, or scanning probes. These techniques are system-specific or sensitive only in a small detection volume, so that practical single spin detection remains an open challenge.

Here, we demonstrate a new method for single-electron-spin-resonance spectroscopy at millikelvin temperatures. It consists in measuring the spin fluorescence signal at microwave frequencies [1, 2] using a microwave photon counter based on a superconducting transmon qubit [3]. In our experiment, individual paramagnetic erbium ions in a scheelite crystal of CaWO4 are magnetically coupled to a small-mode-volume, high-quality factor superconducting microwave resonator to enhance their radiative decay rate [4]. We detect the microwave photon spontaneously emitted by a spin following its excitation with a signal-to-noise ratio of 1.9 in one second integration time. This fluorescence signal shows anti-bunching, proving that it comes from individual emitters [5]. Coherence times up to 3ms are measured, limited by the spin radiative lifetime. The method applies to arbitrary paramagnetic species with long enough non-radiative relaxation time, and offers large detection volumes ($\sim 10\mu m^3$); as such, it may find applications in magnetic resonance and quantum computing.

[1] Albertinale, E. et al. Detecting spins by their fluorescence with a microwave photon counter. Nature **600**, 434– 438 (2021).
[2] L. Balembois, et al. Practical Single Microwave Photon Counter with 10^{-22} W/$\sqrt{Hz}$ sensitivity. arXiv :2307.03614.
[3] Z. Wang, et al. Single-electron spin resonance detection by microwave photon counting. Nature **619**, 276–281 (2023).
[4] R. Lescanne et al. Irreversible Qubit-Photon Coupling for the Detection of Itinerant Microwave Photons. Phys. Rev. X **10**, 021038 (2020).
[5] A. Bienfait et al. Controlling spin relaxation with a cavity. Nature **531**, 74 (2016).

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Squeezed-vacuum techniques for quantum noise reduction in interferometric gravitational-wave detectors

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Interferometric gravitational-wave (GW) detectors like LIGO and Virgo, which opened the GW astronomy era in 2015 with the first GW detection, have observed more than 90 GW signals emitted by the merging of compact objects (black holes and neutron stars), yielding a wealth of scientific results ranging from astrophysics, fundamental physics, and cosmology [1].

However, the sensitivity of these detectors and those of the next generation (which are currently under study) is limited by quantum noise on a substantial fraction of their sensitivity spectrum. In these modified Michelson interferometers, characterized by kilometer-long arms and test masses suspended from multi-pendula chains, quantum noise manifests in two distinct forms : "shot noise," at high frequency, due to statistical fluctuations in the arrival time of photons on the detection photodiode, and "quantum radiation pressure noise," at low frequency, due to quantum fluctuations in the flux of photons striking the suspended mirrors.

Already in the 1980s, Carlton Caves demonstrated that quantum noise in interferometers was ultimately due to quantum fluctuations in the vacuum entering the interferometer's detection port [2]. To reduce this noise, Caves proposed replacing the standard vacuum field with manipulated vacuum states whose amplitude and phase uncertainties (which are equal in ordinary vacuum) were increased and reduced, respectively. For such states, known as squeezed states, Heisenberg's uncertainty principle, affecting the product of phase and amplitude, is still verified, and they are usually represented by ellipses in the plane of the two quadratures (while ordinary vacuum is represented by a circle). If the reduced noise quadrature is aligned with the gravitational wave signal, the result is a reduction in quantum noise.

During the last data-taking period (O3) from 2019 to 2020, these 'squeezed' states were produced and injected into LIGO and Virgo, resulting in an enhanced sensitivity and a significant increase in the number of detected GWs [3, 4]. More sophisticated squeezing techniques are used in the ongoing observation run (O4) [5], and studies are ongoing to reduce quantum noise by a factor of 3 (10 dB of detected squeezing) in a large fraction of the detection band.

In this contribution, after detailing the principles and the main results of quantum noise reduction using squeezing for GW detectors, we present the challenges and research avenues for future-generation gravitational-wave detectors.

[1] LIGO Scientific, the Virgo, the KAGRA Collaborations, "GWTC-3 : Compact binary coalescences observed by LIGO and Virgo during the second part of the third observing run" , arXiv :2111.03606v2.
[2] C. M. Caves, "Quantum-mechanical noise in an interferometer", Phys. Rev. D 23, 1693 (1981).
[3] F. Acernese et al., "Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light", Phys. Rev. Lett. 123, 231108 (2019).
[4] M. Tse et al., "Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy", Phys. Rev. Lett. 123, 231107 (2019).
[5] F. Acernese et al., "Frequency-Dependent Squeezed Vacuum Source for the Advanced Virgo Gravitational-Wave Detector", Phys. Rev. Lett. 131, 041403 (2023)

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Time-frequency quantum metrology

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Hong-Ou-Mandel interferometry takes advantage of the quantum nature of two-photon interference to increase the resolution of precision measurements of time delays. Relying on few-photon probe states, this approach is applicable also in cases of extremely sensible samples and it achieves attosecond-scale resolution, which is relevant to cell biology and two-dimensional materials. Here, we theoretically analyze how the precision of Hong-Ou- Mandel interferometers can be significantly improved by engineering the spectral distribution of two-photon probe states. In particular, we assess the metrological power of different classes of biphoton states with non-Gaussian time-frequency spectral distributions, considering the estimation of both time and frequency shifts. We find that grid states, characterized by a periodic structure of peaks in the chronocyclic Wigner function, can outperform standard biphoton states in sensing applications [1].

After discussing the spectral engineering of photon pairs, we will discuss the use of more general quantum states possessing a higher number of photons for estimating time shifts using the presented intrinsic multimode quantum metrology approach [2]. We will show that the particle-number and time-frequency degree of freedom are intertwined for quantifying the ultimate precision achievable by quantum means. Increasing the number of photons of a large entangled EPR probe state actually increases the noise coming from the frequency continuous variable hence deteriorating the precision over the estimation of a time shift.

[1] N. Fabre and S. Felicetti, Parameter Estimation of Time and Frequency Shifts with Generalized Hong-Ou- Mandel Interferometry, Phys. Rev. A **104**, 022208 (2021).

[2] Eloi Descamps, Nicolas Fabre, Arne Keller, and Pérola Milman Phys. Rev. Lett. **131**, 030801 (2023)

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Metrological witness for non-Gaussian quantum entanglement

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Major efforts are being conducted worldwide for harnessing the power of quantum systems for information processing and computation. Quantum states of light offer a promising candidate platform for those efforts. The latter is due, among others, to their strong resilience to decoherence and its potential for scalability.

Within the framework of continuous variable quantum systems, states can be described by means of quasi-probability distributions in phase space, notably through the Wigner function. It is known that a non-Gaussian statistics with a negative Wigner function, together with quantum entanglement [1], is necessary to develop protocols that can not be simulated efficiently with classical resources. In particular, it has been shown in [2] that not passive separable states, *i.e.* , non-Gaussian states whose entanglement cannot be undone by passive linear optical operations — and, thus, entangled in all mode bases, is needed to reach a quantum advantage in a class of sampling protocols.

In this talk we will present an entanglement witness based on metrological tools and able to detect not passive separable states. We will show that we can use this witness to characterize not passive separability in one and two-photon subtracted states, which are within the reach of current experiments. We will then discuss the effect of losses on the ability of the criterion to work on those states, and show that we find a strong resilience to losses, of up to 50%. This resilience encourages us to find a feasible protocol to test this witness on real experiments.

[1] A. Mari and J. Eisert, "Positive Wigner Functions Render Classical Simulation of Quantum Computation Efficient", Phys. Rev. Lett. **109**, 230503 (2012).

[2] U. Chabaud and M. Walschaers, "Resources for bosonic quantum computational advantage", Phys. Rev. Lett. **130**, 090602 (2023).

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Measurement-induced collective vibrational quantum coherence under spontaneous Raman scattering in a liquid

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Spontaneous vibrational Raman scattering is a ubiquitous form of light–matter interaction whose description necessitates quantization of the electromagnetic field. It is classically considered as an incoherent process because the scattered field lacks any predictable phase relationship with the incoming field [1]. When probing an ensemble of molecules, the question therefore arises: What quantum state should be used to describe the molecular ensemble following spontaneous Stokes scattering? We experimentally address this question by measuring time-resolved Stokes–anti-Stokes two-photon coincidences on a molecular liquid consisting of several sub-ensembles with slightly different vibrational frequencies (Figure 1) [2]. When spontaneously scattered Stokes photons and subsequent anti-Stokes photons are detected into a single spatiotemporal mode, the observed dynamics is inconsistent with a statistical mixture of individually excited molecules. Instead, we show that the data are reproduced if Stokes–anti-Stokes correlations are mediated by a collective vibrational quantum, i.e. a coherent superposition of all molecules interacting with light. Our results demonstrate that the degree of coherence in the vibrational state of the liquid is not an intrinsic property of the material system, but rather depends on the optical excitation and detection geometry. Our work nourishes the debate about the relation between optical coherence and quantum coherence [3] and entanglement [4].

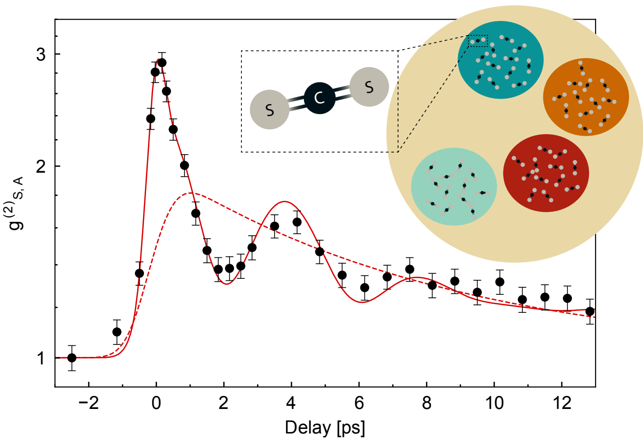

FIG. 1. **Time-resolved Stokes–anti-Stokes correlations.** Full circles represent the measured data points while the solid red line indicates the model prediction. The observed quantum beats are consistent with a macroscopic quantum superposition of four sub-ensembles of CS_2 molecules (inset) sharing a single quantum of vibration. The dotted red line represents the multi-exponential decay that would result from a statistical mixture of single vibrating molecules.

[1] D. A. Long, "The Raman effect: a unified treatment of the theory of Raman scattering by molecules", Wiley (2002).

[2] V. Vento, S. T. Velez, at al., Nat. Commun. **14**, 2818 (2023).

[3] K. Mølmer, "Optical coherence: a convenient fiction.", Phys. Rev. A **55**, 3195 (1997).

[4] A. Karnieli, et al., "The coherence of light is fundamentally tied to the quantum coherence of the emitting particle." Sci. Adv. **7**, eabf8096 (2021).

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Multipartite entanglement in bright frequency combs out of microresonators

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The field of photonic quantum information aims at exploiting quantum states of light to achieve communication and computational tasks that are not classically feasible. The use of high-dimensional entangled states has recently attracted much attention as they enable the possibility of encoding large amounts of information on paired photons answering today's challenge of fibre quantum communication in terms of data capacity, robustness, as well as true securing [1]. On the other hand, quantum integrated photonics on Silicon Nitride (SiN) and on Silicon has now reached a level of maturity allowing the development of practical, flexible, compact, and scalable solutions, holding the promise of technological breakthroughs in quantum information technology. These platforms can allow developing a complete set of flexible integrated functions, ranging from entanglement sources to adjustable configuration circuits, and optical detectors. In this context we investigate high-dimension frequency entanglement generated by non-linear interaction in silicon nitride-based.

We study the generation of multimode entanglement in a SiN micro-ring operating in the continuous-variable regime. Specifically, we analyze the entanglement among different frequency components that are generated via four-wave mixing (FWM) above the oscillation threshold pumped by a continuous-wave laser, resulting in the formation of a frequency comb. These entangled spectral modes are designed to operate in the telecommunication C-band to ensure compatibility with standard fiber-based components. Some pioneering works, all based on the SiN platforms, have been reported, showing bi-partite quantum correlations in intensity [2] or among field quadratures [3].

We present a theoretical model of multimode quantum correlations in bright frequency combs generated in continuous-wave regime by microresonators above threshold. Our analysis shows how these correlations emerge from cascading FWM processes fed by the input pump as well as the generated bright beams. Logarithmic negativity criterion is employed to quantify entanglement between partitions of modes, demonstrating the transition from a bipartite regime just above the oscillation threshold to the multipartite one at higher input pump powers. Due to its generality, our model can be safely used to describe other kinds of non-linear $\chi^{(3)}$ cavities.

To demonstrate the presence of entanglement among the frequency modes, we implemented an experimental setup. A chip fabricated by LETI is pumped by an amplified laser, and the frequency comb at the output is spatially separated using a diffraction grating. Quantum correlations are measured by analyzing the noise level below the shot noise with photodiodes by subtracting the signals corresponding to different frequency beams. Preliminary measurements between the first symmetrical two modes show 1.5 ± 0.1 dB of squeezing, confirming the presence of quantum entanglement. Promising results on intensity squeezing will be presented and discussed in the context of multimode dynamics. The presence of multimode entanglement provides potential opportunities to connect multiple users to a quantum network, increase channel capacity among users, and potentially be exploited for quantum computing purposes [4].

[1] Erhard, Manuel, Mario Krenn, and Anton Zeilinger. "Advances in high-dimensional quantum entanglement." Nature Reviews Physics 2.7 (2020) : 365-381.
[2] Dutt, Avik, et al. "On-chip optical squeezing." Physical Review Applied 3.4 (2015) : 044005.
[3] Vaidya, Varun D., et al. "Broadband quadrature-squeezed vacuum and nonclassical photon number correlations from a nanophotonic device." Science advances 6.39 (2020) : eaba9186.
[4] Menicucci, Pfister et al. "One-way quantum computing in the optical frequency comb." Physical review letters 101.13 (2008).

Development of industrial continuous-variable quantum key distribution systems

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Quantum Key Distribution (QKD) is a field with a potentially major impact on cybersecurity and telecommunications. QKD protocols allow two distant parties to share a secret key independently of the capacities of an eavesdropper. Thanks to quantum physics laws, an attempt to measure the signal on a quantum channel will necessarily introduce a disturbance, thus an eavesdropper will not go unnoticed. The first protocols studied used Discrete Variables (DV), but their implementation requires specific technology, and in particular single-photon detectors. Protocols using so-called continuous variables (CV) instead allow for the use of standard telecommunication components [1]. Recent studies show that high secret key generation rates can be achieved with this technology [2].

Exail coordinates the QKISS project, as part of the development of the European Quantum Communication Infrastructure (EuroQCI), with the help of Thales SIX, LIP6 (CNRS/Sorbonne Université) and Institut d'Optique, with the aim of industrializing CV-QKD systems by 2025. [3]. We have explored different hardware and software configurations to reduce the excess noise and increase the secret key rate [4] of our prototype system. We implement a CV-QKD protocol with heterodyne detection, a true local oscillator (not sent with the signal) and Gaussian modulation. For this system, we designed low distortion modulators, and used optimized fiber optics components for the wavelength of our lasers. Our system also supports two polarizations in emission.

FIG. 1: Photo of the setup: transmitter (down), receiver (up).

The post-processing and error correction are under ongoing development at Thales SIX, thus a homemade, not optimized post-processing is presently used to analyse the data.

We will present the system under development at Exail, the current performance over a distance of 25 km and future evolution and perspectives, including the field testing planned for our demonstration system in 2024.

[1] F. Laudenbach et al. "Continuous-Variable Quantum Key Distribution with Gaussian Modulation-The Theory of Practical Implementations." Advanced Quantum Technologies 1 (1): (2018), 1800011.

[2] F. Roumestan et al., "Experimental demonstration of discrete modulation formats for continuous variable quantum key distribution", arXiv:2207.11702 [quant-ph]

[3] "Quantum Key Industrial SystemS." ec.europa.eu, European Commission. 12/09/2023. https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/how-to-participate/org-details/999999999/project/101091448/program/43152860/details

[4] S. Fossier et al. (2009). "Improvement of continuous-variable quantum key distribution systems by using optical preamplifiers." Journal of Physics B: Atomic, Molecular and Optical Physics. 42. 114014. 10.1088/0953-4075/42/11/114014

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A tight and general finite-size security proof of quantum key distribution

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Quantum key distribution (QKD) is one of the most advanced quantum technologies, having reached a high degree of maturity in its experimental and commercial deployment. Since its conception, the number of different protocols, security proofs and implementations has grown rapidly [1]. In particular, security proofs have evolved in sophistication and applicability, targeting different adversaries in different security models. However, as QKD begins to be deployed in larger and larger settings the reliance on simple and efficient security proofs grows. These developments lead to a major theoretical problem in the security of QKD : how to construct security proofs that are efficient in the finite-size regime, i.e. where both players exchange a finite number of quantum states.

Historically, two approaches to security proofs have been taken. The Shor-Preskill approach originated from the initial security proof of BB84 protocol [2, 3]. It has has been largely successful, yielding good asymptotic key rates and producing positive key rates for small block sizes, however, it is not tight asymptotically and limited in its applicability to protocols that resemble BB84. In parallel, a second more ambitious approach was initiated by Renner [4], who provided a framework to prove the security of generic QKD protocols and achieve the optimal asymptotic Devetak-Winter rate, $R_\infty = H(A|E) - H(A|B)$. This was then combined with the later developed numerical methods to compute asymptotic key-rates for generic protocols [5]. However this approach has been less successful in the finite-size case : the original works based on quantum de Finetti [4, 6] are known to be inefficient. Later works using the entropy accumulation theorem (EAT) [7] improved the finite-size regime but are limited in their applicability to prepare-and-measure protocols.

In the current work, we provide a widely applicable QKD security proof method which yields tight finite-size key-rates against general attacks. Our proof methods achieves three important objectives. Firstly, it is very general and applies to all round-based device-dependent protocols. Secondly, it is the first method that achieves tight finite-size key rates. In particular, when expanded in the number of rounds n, the key rate has a optimal asymptotic and leading order finite-size corrections. Finally, the proof is universal in that there is a systematic way to apply it to each protocol of interest by solving a convex optimisation problem. In the general case, this can be solved efficiently numerically; for simple symmetrical protocols, this can even be done analytically. We illustrate the latter case with the BB84 protocol.

The main idea behind our work is the combination of entropic techniques from quantum information theory and ideas from convex optimisation. Our technical contributions include a new entropy call weighted quantum Renyi entropies (that we used to bound fluctutations in parameter estimation and privacy amplification) and an exact reduction to IID (collective attacks) valid in the finite-size regime. Moreover our protocol has an adaptive property needed to apply the security proof in an efficient way.

By solving a long open-standing theoretical question on the security quantum key distribution, our work now paves the way for the deployment of efficient and practical QKD systems. We provide an efficient method to obtain optimal key rates that can be applied to arbitrary experimental and commercial systems, including protocols that previously were hard to analyse such as Discrete-Modulated CV QKD. A future released open-source software will help hardware researchers implement our methods. Moreover, the universality of our method has several implications for the standardisation of quantum key distribution.

[1] S. Pirandola, U. L. Andersen, L. Banchi, M. Berta, D. Bunandar, R. Colbeck, D. Englund, T. Gehring, C. Lupo, C. Ottaviani, *et al.*, Advances in optics and photonics **12**, 1012 (2020).
[2] P. W. Shor and J. Preskill, Physical Review Letters **85**, 441 (2000).
[3] F. Xu, X. Ma, Q. Zhang, H.-K. Lo, and J.-W. Pan, Rev. Mod. Phys. **92**, 025002 (2020).
[4] R. Renner, *Security of Quantum Key Distribution*, Ph.D. thesis, Swiss Federal Institute of Technology, Zurich (2005), also available as quant-ph/0512258.
[5] A. Winick, N. Lütkenhaus, and P. J. Coles, Quantum **2**, 77 (2018).
[6] M. Christandl, R. König, and R. Renner, Physical review letters **102**, 020504 (2009).
[7] T. Metger, O. Fawzi, D. Sutter, and R. Renner, in *2022 IEEE 63rd Annual Symposium on Foundations of Computer Science*

(FOCS) (IEEE, 2022) pp. 844–850.

Towards large bandwidth spin-wave AFC storage in ^{171}Yb^{3+} :Y_2SiO_5

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Quantum repeaters are key building blocks for long distance quantum communication networks. Rare-earth ion crystals are a promising platform for quantum memories as they offer large multiplexing capabilities. Among them, Y_2SiO_5 crystals doped with ^{171}Yb^{3+} ions is a promising candidate as it benefits from large zero-field splittings and low coupling to magnetic noise. We measured coherence time as long as 10 ms for a 2.5 GHz spin transition [1] which is particularly long for electronic spins.

We also demonstrated the storage of 1250 temporal modes on an optical transition during 25 μs using the atomic frequency comb protocol [2].

In order to realize on-demand storage for longer duration (so-called spin-wave storage), one has to use the spin transitions and to coherently drive them. A tunable lumped-element microwave resonator has been designed to drive transitions up to 3 GHz. Efficient optical pulses also have to be produced to transfer coherences from the optical transition to spin transitions.

We here show recent data of spin-wave storage slightly beyond 1 ms with an AFC bandwidth of 100 MHz [3]. Up to now, we use the simplest sequence of two MW π pulses to deal with spin inhomogeneous brodening. We also exploited that efficient lambda-systems can be tailored in ^{171}Yb^{3+} :Y_2SiO_5 thanks to the branching ratio table being dependent on the polarization of the laser light, an effect of the electronic nature of the hyperfine states. This way, we optimized the Rabi frequency of both the input/output and control fields, which is key to reaching large bandwidths. Our goals for future experiments are to increase the memory lifetime by dynamical decoupling, to explore different optical preparations to increase our total bandwidth to up to 280 MHz, and to optimize our spin-wave storage over the full bandwidth of our memory.

[1] L. Nicolas et. al., "Coherent optical-microwave interface for manipulation of low-field electronic clock transitions in ^{171}Yb^{3+} :Y_2SiO_5", npj Quantum Inf. **9**, 21 (2023).

[2] M. Businger et. al., "Non-classical correlations over 1250 modes between telecom photons and 979-nm photons stored in ^{171}Yb^{3+} :Y_2SiO_5", Nat. Com. **13**, 11-20 (2022).

[3] M. Businger, "^{171}Yb^{3+} :Y_2SiO_5 for quantum memory applications", PhD thesis, University of Geneva (2022).

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Towards quantum control of an ultracoherent mechanical resonator with a fluxonium qubit

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Nowadays, the state-of-the-art chip-scale phononic-crystal membrane flexural modes can achieve lifetimes over 100 s and coherence times in the order of seconds in a thermal environment at 10 mK [1]. It can be achieved using softly-clamped silicon-nitride membranes (typically in the MHz frequency range). The strong coupling between these outstanding mechanical resonators and superconducting qubits (typically in GHz frequency range), one of the most promising platform for scalable quantum computers, has been a long-pursued goal, since it could open the door to novel quantum technology applications, like record-beating quantum memories, microwave-optical quantum transducers [2] or even fundamental tests of quantum gravity [3] by placing a membrane mode in a quantum superposition.

The main challenge to overcome is reducing the wide frequency difference (typically 10^3) between both quantum devices. Inspired by recent works [4], our group has proposed a novel coupling scheme to finally turn the dream into a reality. We have developed a heavy fluxonium qubit which is highly sensitive to a drive charge at a frequency as low as 1.8 MHz, achieving state-of-the-art coherence times for such a qubit architecture [5]. Additionally, we are capable of producing phononic crystal membranes with a large defect mode that can be capacitively coupled to this qubit.

During my presentation, I would like to share the findings of our recent research on the qubit [5], explaining how we successfully developed a charge-sensitive qubit with a competitive decoherence time. Furthermore, I will discuss how this qubit enables us to couple it with a phononic-crystal membrane. Figure 1 provides an example of such a membrane.

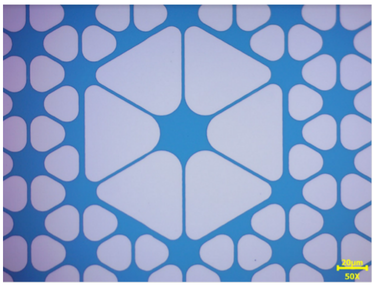

FIGURE 1 – Example of the phononic-crystal membrane utilized in our research group. This particular membrane is fabricated from silicon nitride (SiN) and measures 700 μm in both height and width, with a thickness of 100 nm. The defect is positioned at the center and its size is ensuring that the defect modes fall within the phononic-crystal bandgap.

[1] A Y. Tsaturyan, et al. Nat. Nanotech. 12, 776 (2017)
[2] R. W. Andrews, et al. Nat. Phys. 10, 321 (2014)
[3] M. Gely and G. Steele, arXiv :2004.09153 (2021)
[4] J. J. Viennot, X. Ma, and K. W. Lehnert, Phys. Rev. Lett. 121 (2018) 183601
[5] S. Deléglise, et al. arXiv :2307.14329 (2023)

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Mitigating crosstalk errors by randomized compiling : Simulation of the BCS model on a superconducting quantum computer

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No quantum computer is perfect. To protect quantum information, one can in principle use quantum error corrections, where one transfers the information from one qubit to an entangled system of several qubits and makes adaptive corrections. However, for available noisy, intermediate-scale quantum computers, standard error correction is not feasible. Instead, one uses error-mitigation algorithms that suppress errors by statistically analyzing measurements obtained after running a noisy quantum computer many times. For this to work, one must know the nature of the noise, something that is usually not the case. The biggest challenge is related to quantum operations involving two qubits.

In this talk, I will introduce an approach that transfers coherent noise to incoherent noise, dubbed randomized compiling or Pauli twirling [1]. Emphasis is put onto an extension we have developped [2] which account for crosstalk effects, i.e. operations where neighbouring qubits get accidentally perturbed when a gate is applied to two other qubits. Crosstalk errors, stemming from CNOT two-qubit gates, are a crucial source of errors on numerous quantum computing platforms. For the IBMQ machines their magnitude is usually underestimated by the benchmark protocols provided by the manufacturer. Our RC protocol turns coherent noise due to crosstalk into a depolarising noise channel that can then be treated using established error mitigation schemes such as noise estimation circuits [3]. We apply our approach to the quantum simulation of the non-equilibrium dynamics of the Bardeen-Cooper-Schrieffer (BCS) Hamiltonian for superconductivity, a particularly challenging model to simulate on quantum hardware because of the long-range interaction of Cooper pairs. With 135 CNOT gates, we work in a regime where crosstalk, as opposed to either trotterization or qubit decoherence, dominates the error. Our twirling of neighbouring qubits is shown to dramatically improve the noise estimation protocol without the need to add new qubits or circuits and allows for a quantitative simulation of the BCS model.

[1] J. Wallman and J. Emerson, Noise tailoring for scalable quantum computation via randomized compiling, Physical Review A **94** 052325 (2016)

[2] H. Perrin and al, Mitigating crosstalk errors by randomized compiling : Simulation of the BCS model on a superconducting quantum computer, arXiv :2305.02345 (2023)

[3] M. Urbanek, B. Nachman, V. R. Pascuzzi, A. He, C. W. Bauer, and W. A. de Jong, “Mitigating depolarizing noise on quantum computers with noise-estimation circuits", Physical Review Letters **127** 270502, (2021)

Quantum Density Functional Theory on Qudit-based device

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Abstract

*Speaker

Carbon Nanotube Oscillator as a Nanomechanical Qubit

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Abstract

*Speaker

From cavity-protected atomic ensemble to single atom array in a microcavity

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Multiple quantum emitters coupled to a single cavity mode appear in many situations, ranging from quantum technologies to polaritonic chemistry. While the ideal case of identical emitters is well-understood in terms of symmetric states and polaritons, for practical situations involving inhomogeneous frequency distributions, this simple picture breaks down and new features emerge. By harnessing precise control within a strongly coupled cold-atom system [1], we observe the transition from disorder to a polaritonic regime [2]. Remarkably, polaritons in this regime exhibit significantly narrower linewidths than the atomic frequency distribution, as predicted in the context of cavity protection [4, 5]. Our study also demonstrates the spectral engineering of cavity-protected polaritons, with potential applications in quantum networks.

In our most recent work, we have combined atom-tweezers manipulation with cavity-QED interaction within the strong coupling regime. This new generation of CQED experiment enables precise control over atom ensembles down to the single atom level, paving the way for applications in multiparameter quantum metrology [3] and quantum simulation involving cavity-mediated long-range interactions [4, 5].

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[1] S. Garcia, F. Ferri, J. Reichel, and R. Long, "Overlapping two standing waves in a microcavity for a multi-atom photon interface," Opt. Express **28**, 15515-15528 (2020)

[2] M. Baghdad, P-A. Bourdel, S. Schwartz, F. Ferri, J. Reichel, and R. Long, "Spectral engineering of cavity-protected polaritons in an atomic ensemble", Nat. Phys. **19**, 1104–1109 (2023).

[3] R. Houdré, R. P. Stanley, and M. Ilegems, "Vacuum-field Rabi splitting in the presence of inhomogeneous broadening : Resolution of a homogeneous linewidth in an inhomogeneously broadened system", Phys. Rev. A **53**, 2711 (1996)

[4] I. Diniz, S. Portolan, R. Ferreira, J. M. Gérard, P. Bertet, and A. Auffèves, "Strongly coupling a cavity to inhomogeneous ensembles of emitters : Potential for long-lived solid-state quantum memorie", Phys. Rev. A **84**, 063810 (2011)

[5] Z. Kurucz, J. H. Wesenberg, and K. Mølmer, "Spectroscopic properties of inhomogeneously broadened spin ensembles in a cavity", Phys. Rev. A **83**, 053852 (2011)

[6] M. Gessner, A. Smerzi, and L. Pezzè, "Multiparameter squeezing for optimal quantum enhancements in sensor networks", Nat Commun **11**, 3817 (2020).

[7] T. Botzung, D. Hagenmüller, S. Schütz, J. Dubail, G. Pupillo, and J. Schachenmayer, "Dark state semilocalization of quantum emitters in a cavity", Phys. Rev. B **102**, 144202 (2020).

[8] J. Dubail, T. Botzung, J. Schachenmayer, G. Pupillo, and D. Hagenmüller, "Large random arrowhead matrices : Multifractality, semilocalization", Phys. Rev. A **105**, 023714 (2022).

Deterministic freely propagating photonic qubits with negative Wigner functions

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Engineering quantum states of free-propagating light is of paramount importance for quantum technologies. Coherent states ubiquitous in classical and quantum communications, squeezed states used in quantum sensing, and even highly-entangled cluster states studied in the context of quantum computing [1] can be produced deterministically, but they obey quasi-classical optical field statistics described by Gaussian, positive Wigner functions. Fully harnessing the potential of many quantum engineering protocols requires using non-GaussianWigner-negative states [2], so far produced using intrinsically probabilistic methods.

We will present the first fully-deterministic preparation of non-Gaussian Wigner-negative free propagating optical quantum states[3]. In our setup, a small atomic cloud placed inside a mediumfinesse optical cavity and driven to a highly-excited Rydberg state acts as a single two-level collective "superatom" [4]. We coherently control its internal state, then map it onto a free-propagating light mode to produce an optical qubit $\cos(\theta/2)\,|0\rangle + \sin(\theta/2)\,|1\rangle$ encoded as a quantum superposition of 0 and 1 photons. Its single-photon character is revealed by photon correlation measurements showing strong antibunching with a residual 0.5% probability of having two photons per pulse. The generated states are emitted in the desired spatio-temporal mode with a high 60% efficiency. Using an homodyne tomography we measure the density matrix leading to the Wigner functions displayed on Fig.1. In agreement with theoretical predictions, these functions are quadrature-squeezed for small qubit rotation angles θ, and develop a negative region when θ approaches π and the one-photon component becomes dominant. Our platform featuring a new approach of cavity quantum electrodynamics realizes a long sought goal of quantum optics, while holding promises for photonic quantum engineering applications.

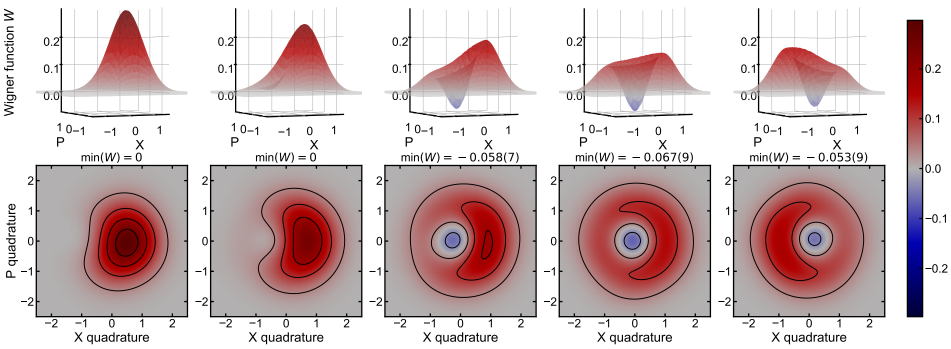

FIGURE 1. Homodyne tomography of the optical qubit, first and second rows show two- and three dimensional color-mapped representations of Wigner functions over quadrature phase space, sorted column wise by increasing qubit rotation angle θ with the measure of one-photon population $p(n = 1)$ of the density matrix

[1] M. V. Larsen et al, Deterministic generation of a two-dimensional cluster state, Science 366, 369 (2019).
[2] M. Walschaers, Non-Gaussian quantum states and where to find them, PRX Quantum 2, 030204 (2021).
[3] V. Magro et al, Deterministic freely propagating photonic qubits with negative Wigner functions, Nat. Photon. 17, 688–693 (2023).
[4] J. Vaneecloo, S. Garcia, A. Ourjoumtsev, Intracavity Rydberg superatom for optical quantum engineering : Coherent control, single-shot detection, and optical π phase shift, Phys. Rev. X 12, 021034 (2022).

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Poster session 1 (Wed. 22^{nd}): Quantum Communications (QCOM)

Millikelvin photon-counting quantum optomechanics and quantum communication with gallium arsenide disk resonators

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During the last decade, there has been several demonstrations of mechanical oscillators put close to their ground state, which is the state of minimal energy dictated by quantum mechanics. Starting from the mechanical ground state, it has been showed both theoretically and experimentally [1] that the physics of optomechanics allows manipulating the quantum state of a mechanical mode at the single phonon level.

We will discuss the feasibility of single-phonon heralding schemes for real-world applications such as the quantum teleportation of an arbitrary photonic qubit to a phononic superposition of two micromechanical oscillators (Fig. 1, left panel) [2], as well as the potential of gallium arsenide disk resonators for this type of experiments (Fig. 1, right panel). We designed and built a cryogenic experimental setup that allows measurements at milliKelvin temperatures and will show our experimental results on cooling the fundamental GHz breathing mode of a 1.3 um radius disk close to its ground state.

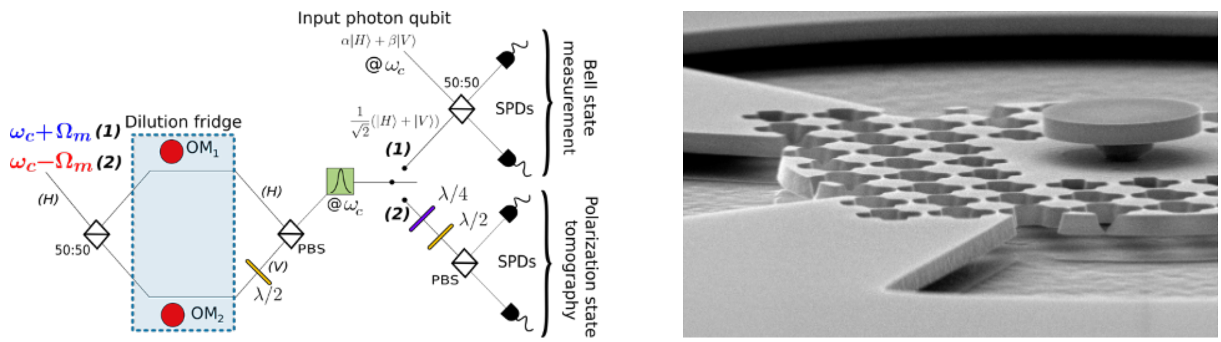

FIGURE 1. Left : Principle of the proposed discrete-variable quantum teleportation scheme. Right : SEM image of a nanofabricated optomechanical disk resonator on a patterned membrane to mitigate mechanical loss.

[1] S. Barzanjeh, et al, Optomechanics for quantum technologies, Nat. Phys. **18**, 15-24 (2022).
[2] S. Pautrel, Z. Denis, J. Bon, A. Borne, and I. Favero, Optomechanical discrete-variable quantum teleportation scheme, Phys. Rev. A **101**, 063820 (2020).

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Magneto-optical time-resolved photoluminescence experiments on G-center ensembles in silicon

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Silicon is the major semiconductor of the information society. It is at the heart of devices in microelectronics and computer technology, and as such one of the most desired platforms for the development of next-generation applications in quantum technologies. On one hand, individual dopants and gate-defined quantum dots have already emerged for implementing electrical qubits in silicon. On the other hand, the literature is still very sparse on silicon-based quantum devices harnessing individual optically active qubits for quantum communications and quantum integrated photonics. Recent studies demonstrating the single-photon emission from several families of isolated individual near-infrared color centers in silicon [1–4] including single spin initialization through optical pumping [5], could open up new perspectives. However, coherent control of a single spin interfaced with light is yet to be demonstrated in silicon.

In this work, we focus on the G center in silicon, a well-known defect recently observed at single scale [6], which possesses a telecom emission and a metastable electron spin triplet that has been detected optically on ensembles in the 80s [7]. Here we present magneto-optical time-resolved experiments carried out on G center ensembles to investigate the energy structure of the metastable spin triplet level. These results are a first step towards the optical detection of the magnetic resonance of the G center in silicon down to the single defect scale.

[1] W. Redjem*, A. Durand* et al., *Nat. Electron.* **3**, 738-743 (2020).
[2] M. Hollenbach et al., *Opt. Express* **28**, 26111-26121 (2020).
[3] A. Durand et al., *Phys. Rev. Lett.* **126**, 083602 (2021).
[4] Y. Baron*, A. Durand* et al., *ACS Photonics* **9**, 2337-2345 (2022).
[5] D. Higginbottom et al., *Nature* **607**, 266-270 (2022).
[6] Y. Baron*, A. Durand* et al., *Appl. Phys. Lett.* **121**, 084003 (2022).
[7] M. Lee et al., *Phys. Rev. Lett.* **48**, 37-40 (1982).

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Entanglement-Enabled Adaptive Optics

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Adaptive optics (AO) has revolutionized imaging in applications ranging from astronomy to microscopy by enabling the correction of optical aberrations. In label-free microscopes, however, conventional AO methods are limited due to the absence of guidestar and the need to select an optimization metric specific to the type of sample and imaging process being used. Here, we propose a AO approach that exploits entanglement between photons to directly access and correct the point spread function (PSF) of the imaging system. This guidestar-free method is independent of the specimen and imaging modality. We demonstrate the imaging of biological samples in the presence of aberrations using a bright-field imaging setup operating with a source of spatially-entangled photon pairs. We show that our approach performs better than conventional AO in correcting certain types of aberrations, particularly in cases involving significant defocus. Our work improves AO for label-free microscopy, and could play a major role in the development of quantum microscopes, in which optical aberrations can counteract the advantages of using entangled photons and undermine their practical use.

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Quantum photonics with colour centres in diamond

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In this work, we will present our latest work on the photoluminescence properties of an ensemble and of single colour centres in nanodiamonds. The colour centres we are interested in are defect centres made of silicon-vacancies (Si-V) and germanium-vacancies (Ge-V) emitting in the visible range. The nanodiamonds are grown by the high pressure-high temperature (HPHT) method and are of high quality [1]. We will present room temperature as well as low temperature spectroscopy of such objects and the dependence of magnetic field, power and polarisation. Spin manipulation will also be presented. Recent results tend to demonstrate that these emitters have similar properties than the ones found in other systems such as quantum dots. We will show that these objects are promising for quantum photonics first by demonstrating that they can emit single photons and we will show that spectroscopy provides good evidence that these quantum emitters have the potential to provide indistinguishable photons. We wil also present our latest results on the integration of a single photon source with a photonic waveguide made of glass using the ion-exchange technique [2,3]. A first prototype of an integrated single photon source has been pigtailed with an optical fibre and works at room temperature [4].

Finally, after presenting results on integrating colloidal nanocrystals, we will show promising results towards integrating single nanodiamonds containing colour centres [7] and how it can lead to positing these nanoemitters with optical waveguides. We will also demonstrate the potential for these nanoemitters for future quantum photonics experiments where the coupling of several emitters could be done.

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[1] M. Nahra *et al.*, "Single germanium vacancy centers in nanodiamonds with bulk-like spectral stability", AVS Quantum Sci. **3**, 012001 (2021).
[2] X. Xu *et al.*, "Towards the Integration of Nanoemitters by Direct Laser Writing on Optical Glass Waveguides", Photonics Research 8, 1541 (2020).
[3] D. Ge *et al.*, "Hybrid plasmonic nano-emitters with controlled single quantum emitter positioning on the local excitation field", Nat. Com. **11**, 3414 (2020).
[4] To be submitted.

Towards demonstration of multipartite entanglement-based quantum communication protocols

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In recent years, significant efforts have been made towards establishing a quantum network that can safely connect remote quantum systems [1]. This includes searching for the most pertinent communication and cryptographic protocols and studying the type of advantages these new technologies could bring us. In order to find what a quantum network could look like at its full potential, one of the aspects which is worth exploring is how good of a tool entanglement, arguably one of the most relevant features of quantum technologies, can be for these new applications.

Photonics based platforms, although inherently probabilistic due to the non-interactive nature of photons, are highly robust against decoherence. Additionally, light, as the most natural choice for distributing information, makes for a very promising platform to test communication protocols in a quantum network scenario. In particular, the photon's polarization degree of freedom has been widely used to encode information and, when combined with a Sagnac interferometer, it has consistently allowed for the generation of very high fidelity Bell pairs, generated via spontaneous parametric downconversion (SPDC) in a non-linear crystal.

Recently, as a first characterization and use of our polarization entangled photon pair source in a Sagnac configuration, we experimentally certified the transmission of a qubit through an untrusted quantum channel [2]. This protocol considers a two-party communication scenario, where Alice wants to send a qubit, ρ_i, to Bob through a quantum channel they have no control over, without placing too much trust on the underlying system. It provides a bound on the fidelity of the state Bob received, ρ_o, to the state Alice initially sent, ρ_i, based on the violation of a Bell test of a set of probe entangled states shared between Alice and Bob, over the untrusted channel. Such a protocol can be used to certify several types of transmission links, required in a network.

In order to move beyond two-party communication, such entangled pairs can be fused into a larger dimension entangled state, namely the Greenberger–Horne–Zeilinger state, that is of particular importance for the implementation of multipatite quantum communication protocols [3] [4]. As we move towards this goal, we need to guarantee a high level of indistinguishability between the interfering photons. For this reason, our new design for a compact and high fidelity GHZ source is based on a layered Sagnac, implemented by spatially multiplexing the pump beam and therefore generating two pairs of entangled photons, one in each layer, in the same crystal and under the same conditions before fusing them into a GHZ. In recent preliminary results, we have estimated a fidelity of 99.4% (98.7%) for the top (bottom) layer pair to the Bell state, which is promising for achieving high fidelity GHZ states. This will open the way to the demonstration of advanced quantum networking protocols.

[1] S. Wehner, D. Elkouss, and R. Hanson, "Quantum internet : A vision for the road ahead", Science, Vol 362, Issue 6412 (2018).

[2] S. Neves, L. dos Santos Martins, V. Yacoub, P. Lefebvre, I. Šupić, D. Markham, and E. Diamanti, "Experimental certification of quantum transmission via bell theorem", arXiv :2304.09605 (2023).

[3] W. McCutcheon, A. Pappa, B. A. Bell, A. McMillan, A. Chailloux, T. Lawson, M. Mafu, D. Markham, E. Diamanti, I. Kerenidis, J. G. Rarity and M. S. Tame, "Experimental verification of multipartite entanglement in quantum networks", Nat Commun 7, 13251 (2016).

[4] A. Pickston, Joseph H., Andrés U., Federico G., Massimiliano P., Christopher L. M., Peter B., Francesco G. and Alessandro F., "Conference key agreement in a quantum network", npj Quantum Inf 9, 82 (2023).

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Design of a Silicon Photonics Circuit for Quantum Cryptography Applications

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The One Time Pad is an encryption method that has been proven to be information-theoretically secure. The correct operation of such a method relays on a randomly generated, unique secret key that must be distributed throughout the network for further decryption. The Quantum Key Distribution (QKD) protocol, initially proposed by Bennet and Brassard in 1984 [1], offers an intrinsically secure solution for the secret key distribution over an optical network, exploiting quantum properties of light.

A number of practical implementations relying on different quantum observables have been already proposed. In 2018, Boaron et al. [2] demonstrated an implementation of QKD using a three-state time-bin protocol working on a 421-km long optical link.

Within this context, our work aims at integrating the source (Alice) in the perspective of implementing the three-state time-bin protocol on a Silicon Photonics (Si-Phot) circuit. Si-Phot allows the integration of electrically-driven devices on optical chips, i.e., devices where a light signal is guided within a Si waveguide and manipulated through electrical signals, relying on the already existing advanced semiconductors fabrication techniques.

In particular, we work on a photonic chip where Alice's source is implemented. Our hypothesis is that, considering such a setup, we are able to deploy a small-footprint, compact device showing competitive performances in realistic instances of QKD networks.

The design of this chip requires the integration of devices in three main stages. A delay line, implemented through an unbalanced, phase-stabilized interferometer. A high-speed intensity modulation stage, implemented through high-speed phase modulators relying on PN carrier-depletion structures, which were proven to be able to provide high bit rates [3], ensuring a high Secret Key Rate. Finally, thermal phase shifters and PiN carrier-injection structures are used for a variable attenuation stage with the purpose of attenuating the coherent pulses down to single-photon regime. The fabrication is made with the Silicon Photonics platform at STMicroelectronics.

The devices on the silicon chip are controlled via a printed circuit board (PCB), which is designed to operate at high speed to drive the intensity modulation stage.

[1] C. H. Bennett and G. Brassard. "Quantum cryptography : Public key distribution and coin tossing" Proceedings of IEEE International Conference on Computers, Systems and Signal Processing, volume 175, page 8. New York, 1984.

[2] Boaron, Alberto, et al. "Secure quantum key distribution over 421 km of optical fiber." Physical review letters 121.19 (2018) : 190502.

[3] Rahim, Abdul, et al. "Taking silicon photonics modulators to a higher performance level : state-of-the-art and a review of new technologies." Advanced Photonics 3.2 (2021) : 024003.

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Spectrally multimode squeezed states generation at telecom wavelengths

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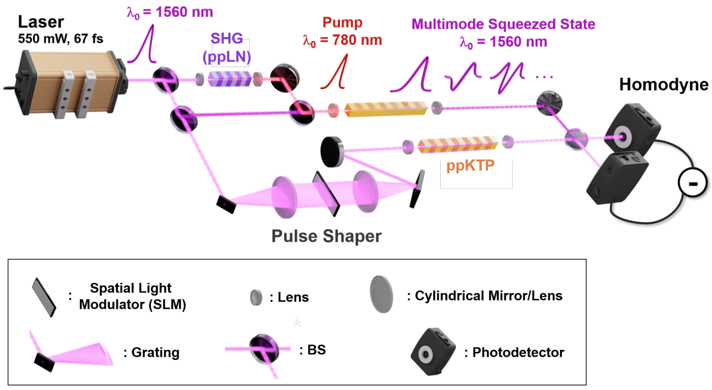
Continuous variable encoding of quantum information requires the deterministic generation of highly correlated quantum states of light in the form of quantum networks, which, in turn, necessitates the generation of a large number of squeezed modes [1]. In this work, we present an experimental demonstration of a source that generates spectrally multimode squeezed states of light at telecommunication wavelengths [2]. Generation at such wavelengths is especially important, as it can enable quantum information, communication, and sensing beyond the laboratory scale. We achieve state generation using a single-pass Spontaneous Parametric Down Conversion (SPDC) process in a periodically-poled KTP waveguide pumped with the second harmonic of a femtosecond laser [3]. Our measurements reveal significant squeezing in more than 21 frequency modes, with a maximum squeezing value exceeding 2.5 dB. Furthermore, we demonstrate multiparty entanglement across 8 individual frequency bands by measuring the covariance matrix of their quadratures. Finally, we use reconfigurable mode-selective homodyne detection to shape the output into cluster states of various configurations. This result paves the way for a scalable implementation of continuous variable quantum information protocols at telecommunication wavelengths, particularly for multiparty and entanglement-based quantum communications. Moreover, the single-pass configuration is compatible with additional pulse-by-pulse multiplexing, which can be utilized to construct the necessary three-dimensional entangled structures for quantum computing protocols [4–6].



[1] N C Menicucci, P van Loock, M Gu, C Weedbrook, T C Ralph, and M A Nielsen, "Universal quantum computation with continuous-variable cluster states", Phys.Rev. Lett. **97**, 110501 (2006).

[2] V. Roman-Rodriguez, D. Fainsin, G. L. Zanin, N. Treps, E. Diamanti, and V. Parigi, "Spectrally multimode squeezed states generation at telecom wavelengths", arXiv 2306.07267 (2023).

[3] V. Roman-Rodriguez, B. Brecht, S. Kaali, C. Silberhorn, N. Treps, E. Diamanti, and V. Parigi, Continuous variable multimode quantum states via symmetric group velocity matching, New J. Phys. 23 043012 (2021).

[4] T. Kouadou, F. Sansavini, M. Ansquer, J. Henaff, N. Treps and V. Parigi, "Spectrally shaped and pulse-by-pulse multiplexed multimode squeezed states of light", APL Photonics, 8, 8 (2023)

[5] M V Larsen, X Guo, C Breum, J Neergaard-Nielsen, and U L Andersen, Deterministic generation of a two-dimensional cluster state, Science (2019).

[6] W Asavanant, Y Shiozawa, S Yokoyama, B Charoensombutamon, H Emura, R N Alexander, S Takeda, J Yoshikawa, N C Menicucci, H Yonezawa, A Furusawa, Generation of time-domain-multiplexed two-dimensional cluster state, Science (2019).

Resource-efficient generation of 6-photon linear cluster states from quantum dot single photon sources

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Entanglement is a key resource to scale up photonic quantum technologies pertaining to quantum computing or quantum communications [1], [2]. The generation of multiphoton entangled states enables for example redundancy of quantum information and thus robustness over optical losses and errors. The generation of such sates are also an enabling element for Measurement-Based Quantum Computing [3].

We present a resource-effective approach to generate of large states of entangled photons, known as photonic linear cluster states. We use a bright single photon source, here an InAs quantum dot embedded within a micropillar cavity [4], and a fibered entangler (See Fig. 1a) [5], composed of a polarizing beamsplitter and a fiber delay loop. We demonstrate entanglement of up to 6 photons in a linear cluster state at a rate of 2 mHz. The success of the method relies on a high brightness source ($B_{fibered} = 12\%$) of pure ($g^{(2)}(0) = 2\%$) and indistinguishable photons ($M = 90\%$), a sufficiently transmissive fibered delay loop setup ($T_{setup} = 50\%$) and two high efficiency single photon detectors ($\eta_{detectors} = 90\%$). Our method is probabilistic but highly resource efficient, allowing for better scaling ratio than path encoded protocols.

We demonstrate in such a resource efficient way the generation of entangled states (Fig. 1b), reaching for the first time 6 photons This work can be pushed further by further reducing the optical losses of the overall setup. The entanglement of our 6 photon linear cluster is certified by our visibility measurement. We'll explain how a full tomography of the produced state can be achieved and how such cluster states resource efficient methods can be combined with deterministic schemes for forefront quantum computing tasks/applications.

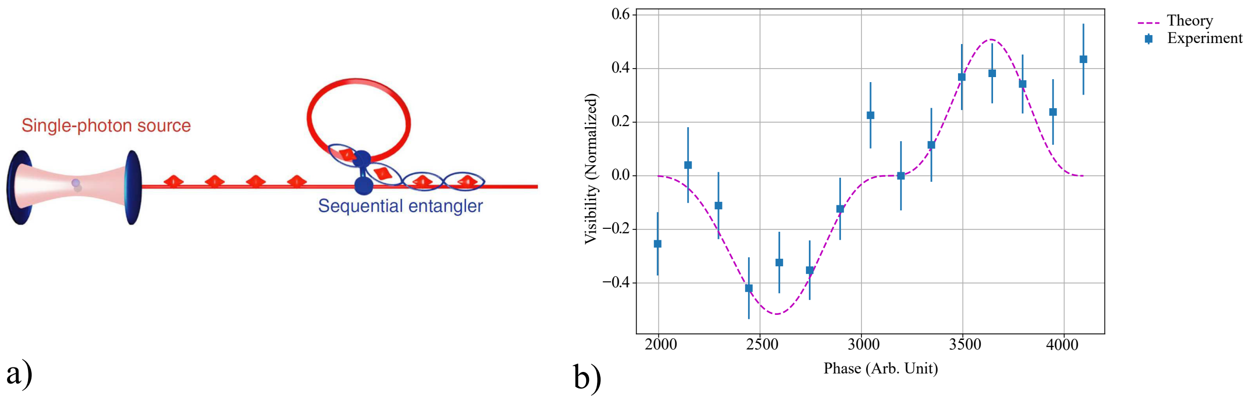

Figure 1 : a) Principle of resource efficient linear cluster state generation [5] - Our source and implementation enable 6-photon entanglement thanks to $B_{fibered} = 12\%$ and $T = 50\%$. b) 6-photon entanglement measurement - A visibility higher than 0.3 ensures entanglement preserved through the state - Experimental value of $0.5(0.1)$. The theoretical model considering 86% Hong-Ou-Mandel visibility predicts a 0.55 visibility in agreement with the measurement.

* These authors contributed equally to this work.

[1] S. Bartolucci et al., "Fusion-based quantum computation", Nat. comm. **14**, 912 (2021).
[2] P. Hilaire, E. Barnes and S. Economou, "Resource requirements for quantum computation using photonic graph stats generated from a few matter qubits", Quant. Journal **5**, 397 (2021).
[3] R. Raussendorf, H. J. Briegel, "A one-way quantum computer", Phys. Rev. Lett. **56**, 5188 (2001).
[4] P. Senellart, G. Solomon and A. White, "High-performance semiconductor quantum-dot single-photon sources", Nat. nanotech. **12**, 1026-1039 (2017).
[5] D. Istrati et al., "Sequential generation of linear cluster states from a single photon emitter", Nature Comm. **11**, 5501 (2020).

Experimental implementation of simulation secure quantum oblivious transfer

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Oblivious transfer (OT) is a prominent two-party cryptographic primitive in which the sender transmits one of potentially many pieces of information to the receiver but remains oblivious to which part (if any) was received, and the receiver learns only their selected part of the information without any chance to learn all the pieces. It is an essential building block of secure multiparty computing which enables private and secure computation on distributed data.

An early quantum version of OT exploited the randomness in BB84 states [1] along with bit commitment schemes. However, the type of commitments necessary for the proof of security are strong enough, and its classical implementation already implies (classical) OT. In recent work [2, 3], the authors independently showed how to construct quantum bit-commitments with strong security guarantees from One Way Functions, which classically do not imply OT. With these quantum commitments in hand, they show quantum OT from One Way Functions with simulation security, which is important for composability.

In this work, we are interested in the experimental demonstration of the protocol proposed in [4]. The main reason for choosing this protocol is the black box use of the quantum One Way Functions, which only requires an oracle access to its input and output.

Our experimental demonstration is based on a BB84-type system, with single photons heralded from a Spontaneous Parametric Down Conversion correlated photon pair source. All the classical cryptographic primitives involved in the protocol were implemented in Python. The protocol is built mainly from two black box compilers achieving extractability and equivocality. In the measurement check step of the CK88 protocol in [1], we use the extractable equivocal compiler. A security parameter, λ, is defined for each step ; the higher the security parameter, the stronger the security. When setting the security parameters $(\lambda_{ck88}, \lambda_{eq2}, \lambda_{ex}, \lambda_{eq1}, \lambda_{naor})$ (where the latter refers the Naor bit commitment scheme [6]) to (512, 1, 4, 1, 256) we had a running time of ≈ 15 mins with noiseless BB84 states but it can scale up to ≈ 40 mins with noisy states since we need a larger number of states and more runs in each layer, thus increasing the λ parameters.

Our results highlight the gap between the asymptotic security parameters involved in the theoretical protocol and the ones that we can achieve experimentally within a reasonable time considering the noise present in the quantum state generation and measurements. This suggests that the current protocol needs to be modified to account for noise, hence opening the way to practical implementations of quantum-enhanced secure multiparty computing.

[1] Claude Crépeau and Kilian Joe, "Achieving oblivious transfer using weakened security assumptions", Proceedings of the 29th Annual Symposium on Foundations of Computer Science. IEEE Computer Society, 1988.
[2] Dominic Mayers, "Unconditionally secure quantum bit commitment is impossible", Phys. Rev. Lett. 78, 3414 (1997).
[3] H.-K. Lo and H.-F. Chau, "Is quantum bit commitment really possible ?", Phys. Rev. Lett. 78, 3410 (1997).
[4] James Bartusek *et al.*, "One-way functions imply secure computation in a quantum world", Advances in Cryptology–CRYPTO 2021 : 41st Annual International Cryptology Conference, CRYPTO 2021, Virtual Event, August 16–20, 2021, Proceedings, Part I 41. Springer International Publishing, 2021.
[5] Alex. B. Grilo *et al.*, "Oblivious transfer is in MiniQCrypt", Annual International Conference on the Theory and Applications of Cryptographic Techniques. Cham : Springer International Publishing, 2021.
[6] Moni Naor, "Bit commitment using pseudorandomness", Journal of cryptology 4 (1991) : 151-158.

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Blue-green single-photon emission at room-temperature with a CdSe/ZnSe nanowire quantum

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Single-photon sources are key components for communication ultra-secured by quantum physics laws. Accurate synchronization is required for correct operation in telecommunications networks, and thus triggered emission is essential. In this contribution, we present a promising solid-state system able to emit triggered single-photons in the blue-green range at room temperature. This spectral band allows quantum communications both in free space and underwater.

The active element is a CdSe quantum dot (QD) embedded in a bottom-up core-shell ZnSe nanowire (NW) grown by molecular beam epitaxy. The NW shell acts as a waveguide and confines the fundamental optical mode HE11, channelling the photons emitted by the QD along the NW axis. We present a thorough study of a single nanowire using a whole range of characterization thanks to markers made on the growth substrate. The studied NWQD has a base diameter of 140 nm and a length of 5 µm (Fig. a). The conical ending adiabatically expands the guided mode and reduces the divergence angle, thus increasing the collection efficiency. This is confirmed by the far-field diagram (Fig. b) collected along the NWQD axis (Fig. a) where a Gaussian mode profile with small divergence angle is observed. Photo-correlation measurements on the excitonic lines show anti-bunching with $g(0)^{(2)}$ value down to 0.3 (Fig. c) [1]. Complementary measurements done at cryogenic temperature have helped to understand the phenomena that degrade the single-photon purity at room temperature. We found that the single-photon emitter shows a promising brightness with a potential emission rate of 13 MHz with a 76 MHz excitation rate. This work paves the way for development of a practical blue-green single-photon sources operating at non-cryogenic temperatures.

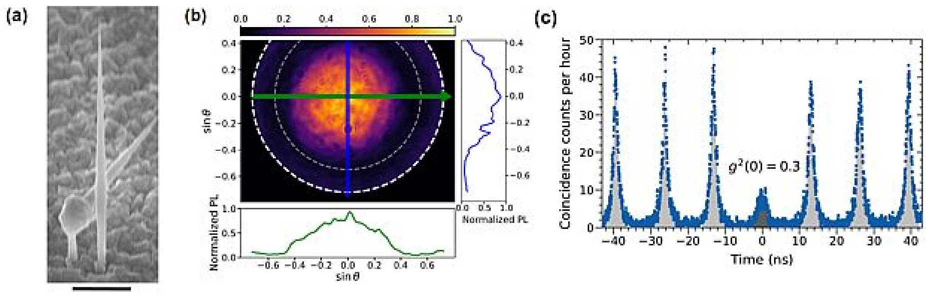

Figure : (a) SEM image of a vertical and tapered ZnSe NW embedding a CdSe QD; (b) Radiation pattern of the QD-NW displayed in (a) through a microscope aperture of NA=0.72; (c) autocorrelation histogram of the NWQD at 300K with a $g^{(2)}(0)$ value of 0.3.

[1] F. Granger et al., Brightness and purity of a room-temperature single-photon source in the blue-green range, Optics Letters Vol. 48, 3833(2023). https ://doi.org/10.1364

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Cavity quantum electrodynamics with color centers in silicon optical microcavities

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Silicon is a major material platform for large-scale quantum photonics, with the integration of hundreds of components in cm²-scale programmable chips [1]. However, further expansion is challenged by the difficulty to generate single photons on demand in silicon. An ideal solution would be the direct integration of all-silicon single photon emitters into a chip. In this context, the isolation of individual color centers in silicon provides a diversity of candidates to build such a source [2]. By placing a color center inside a silicon-on-insulator (SOI) microcavity, one expects to control its spontaneous emission to build a source of single photons at telecom wavelengths into a well-defined optical mode.

In recent work, we have reported a step in this direction by demonstrating an enhancement by factor 5 of the zero-phonon line (ZPL) of an ensemble of G centers in a microring cavity. Importantly, we showed that this enhancement was caused by Purcell acceleration of zero-phonon emission into a resonant mode. However, the total decay rate was not significantly affected by the ZPL-mode coupling, from which we estimated a poor quantum yield for the G centers [3].

Here, we present cavity quantum electrodynamics (CQED) experiments with an ensemble of W centers in circular Bragg grating cavities. The W center is a tri-interstitial silicon color center created upon self-ion implantation and thermal annealing [4]. Notably, it features a higher quantum yield and higher ZPL fraction than the G center, and is thus more favorable for CQED experiments. We demonstrate an enhancement of the ZPL intensity by a factor of 20 and Purcell acceleration of the total decay rate by a factor of 2. These results are promising for further CQED experiments with individual W centers in SOI microcavities.

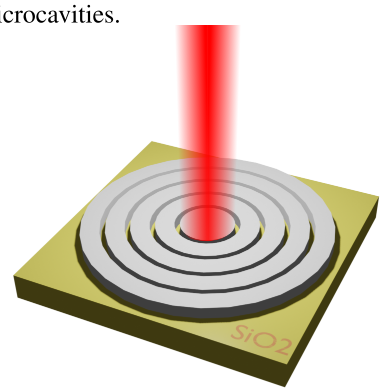

Figure : Illustration of a SOI circular Bragg grating cavity with light emission from W centers into the resonant mode.

[1] J. Wang, F. Sciarrino, A. Laing, et al., "Integrated Photonic Quantum Technologies", Nat. Photonics **14**, 273-284 (2020).

[2] A. Durand, Y. Baron, W. Redjem, et al., "Broad Diversity of Near-Infrared Single-Photon Emitters in Silicon", Phys. Rev. Lett. **126**, 083602 (2021).

[3] B. Lefaucher, J.-B. Jager, V. calvo, et al., "Cavity-Enhanced Zero-Phonon Emission from an Ensemble of G Centers in a Silicon-on-Insulator Microring", Appl. Phys. Lett. **122**, 061109 (2023).

[4] Y. Baron, A. Durand, P. Udvarhelyi, et al., "Detection of Single W-Centers in Silicon", ACS Photonics **9**, 2337-2345 (2022).

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Dynamical mapping of a single spin state into the polarization state of single photons

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An efficient, deterministic light-matter interaction is required to scale future quantum networks. An important milestone is represented by the implementation of conditional operations on flying qubits with a single stationary qubit. As our matter qubit candidate we use a single electron confined in an InAs quantum dot (QD) embedded in an electrically contacted micropillar cavity. The flying qubit is encoded by the polarization state of the incoming photons that interacts with the spin degree of freedom of the confined electron.

In our work, we explore the interference between the reflected light from the cavity and the QD emission, phenomena at the core of large polarization rotations [1]. The system is under the influence of a transverse magnetic field and we study how the reflected polarisation states are affected by the interaction with the single spin. Detecting a first photon with a certain polarization modifies the spin state by performing a projective measurement (Figure 1). While the spin evolves back to the stationary state, we monitor the polarization state of the reflected photons in the Poincaré sphere, which directly translates the spin dynamics in the Bloch sphere.

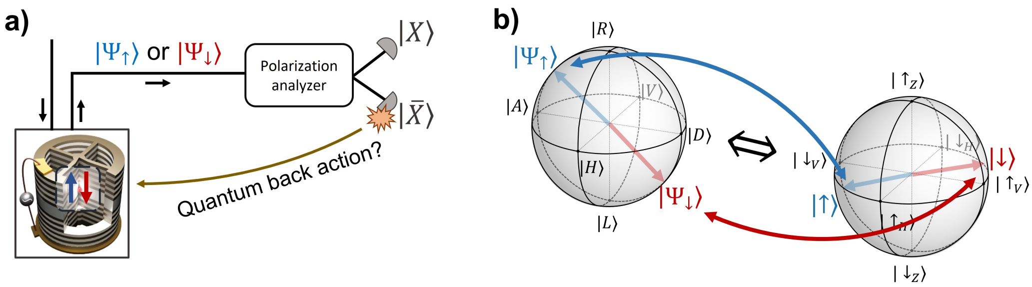

FIGURE 1 – Scheme showing the principle of a measurement backaction. b) Detecting a photon in $|\Psi_\uparrow\rangle$ (resp. $|\Psi_\downarrow\rangle$) ideally projects the spin in $|\uparrow\rangle$ (resp. $|\downarrow\rangle$).

[1] E. Mehdi et al., *arXiv :2212.03767* (2022).

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Toward fully operational quantum key distribution networks using entanglement

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during the last 40 years, quantum key distribution technologies went from Theoretical concepts to large country wide experimental realizations of QKD links, based on prepare and measure protocols. The next step for the development of this technology is to aim toward a fully operational implementation of different protocols, to improve the flexibility of the quantum key distribution process.

In this context, we present the technological aspect of the real-field implementation of the first french quantum key distribution network, using entangled photon pairs [1]. The experiment uses 3 nodes deployed over 50 km of standard telecom optical fiber spanning over the "Métropole Côte d'Azur", where keys are distributed from an entangled photon pair source to two users, following the protocol BBM92 [2]. This fixed fiber architecture allows the comparison of different approaches of entanglement based QKD, using either polarization or time-bin as an observable. Therefore, six QKD stations are developed : two sources of high quality entangled photon pairs (for polarization or energy time entanglement) and two pairs of analyzers, one for each observable. The implementation of those station and, most of all, the interactions between the nodes, requires the development of different tools, to go from a laboratory experiment to a fully deployed, operational and automated QKD link.

First, a synchronization protocol is required to keep paced the clocks of each user, in order for them to measure precisely coincidences. Our implementation only uses photons pairs transmitted through the fiber, which allows synchronization without requiring extra fiber or adding any noise to the quantum channel. It keeps the drift between two distant rubidium atomic clocks under 12 ps at all time, allows an optimal measurement of the photon pairs for the QKD experiment and is compatible with both polarization and time-bin experiments.

Second, a real time post treatment program has to be developed in order to convert the detection event into actual secured cryptographic keys. Real time post treatment is crucial for this kind of experiment, since it allows computing immediately the error rates, ad other security parameters of the link, which can then be used for different active stabilization, required for the link to function.

Finally, building a fully operational and automated link, requires each station to be independent. Therefore, each component used in the source or the analyzers has to be either fully passive, or remotely controllable, which add constraints to the development of the different modules. This allows the program to control automatically each parameter, and optimize continuously the key rate generated by the link.

Finally, we study the feasibility of implementing the time-bin experiment in different architecture. We measure in lab the key rate for links with losses estimated for links up to more than 100 km between users. Furthermore, we measure the feasibility of deploying a high density quantum network, using wavelength multiplexing, and are able to generate up to 36 pairs of independent channels, which could theoretically lead to a 36 users fully connected quantum network.

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[1] Pelet, Yoann, *et al. "Operational real field entangled quantum key distribution over 50 km." arXiv preprint arXiv:2207.14707 (2022).*

[2] Bennett, Charles H., Gilles Brassard, and N. David Mermin. "Quantum cryptography without Bell's theorem." Physical review letters 68.5 (1992): 557.

Experimental demonstration of Continuous-Variable Quantum Key Distribution with a photonic integrated receiver and modular software

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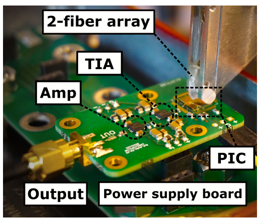
Quantum Key Distribution (QKD) is one of the most prominent and mature tasks of quantum cryptography. It allows two trusted parties, Alice and Bob, to exchange a secret key over a public quantum channel and a public but authenticated classical channel with information-theoretic security, even in the presence of an eavesdropper Eve with power only bounded by the laws of physics.

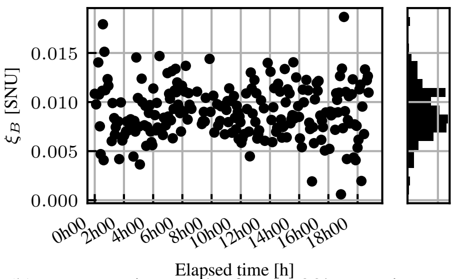
In discrete-variable (DV) QKD protocols, information is encoded on discrete degrees of freedom of quantum states of light (*e.g.* the polarisation of single photons), and systems are mature, have relatively light post-processing and are in general resilient to loss. In continuous-variable (CV) QKD protocols, information is encoded on continuous degrees of freedom such at the quadratures of the electromagnetic field, and hence systems do not require single-photon detection, and work instead with regular photodetectors at room temperature. The latter can work at a significantly higher rate (tens of GHz) than the former ones that are limited to some hundreds of MHz. Another important characteristic is that CV-QKD receivers are easier to integrate than their DV counterparts [1], which allows in principle for an integration of both the transmitter and receiver.

In this work, we present an experiment implementing the GG02 CV-QKD protocol [2] with locally generated Local Oscillator, Optical Single Side Band modulation, and frequency multiplexed pilots. In particular we present the benchmarks of our homemade software, called QOSST, with Gaussian modulated coherent states and distances up to 25 km. Thanks to a symbol rate of 100 MBaud, we are able to reach MBit/s secret key rates with bulk components. Our software is capable of optimizing around 10 DSP (digital signal processing) parameters to ensure the best phase and polarization recovery and excess noise levels, is highly modular, and allows for the use of different hardware platforms such as different receivers.

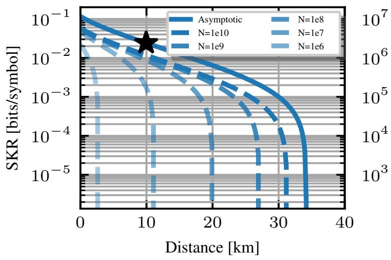
We also present a CV-QKD integrated receiver based on a silicon Photonic Integrated Circuit (PIC) performing the optical mixing and detection part, along with its electronic board featuring an ultra low-noise Trans-Impedance Amplifier (TIA), which is critical to ensure low electronic noise along with a good bandwidth and linearity (see Fig. a). The receiver exhibits good performance as a standalone device : $>$ 20 dB clearance at low frequencies, $\sim$ 200 MHz of bandwidth, $>$ 99% linearity and global efficiency of 26%, and was integrated in our CV-QKD experiment. The system was stable over 20h and reached an excess noise at Bob side $\xi_B = 0.009$ SNU, compatible with secret key rates (SKR) of 485 kbit/s at 23 km (see Fig. b). At 10 km the potential SKR is 2.4 Mbit/s (see Fig. c). This demonstrates the feasibility of using a CMOS compatible, low cost, low size, integrated receiver for CV-QKD.



(a) PIC-based receiver in setup.



(b) Excess noise results for the 20h experiment.



(c) Projected SKR at asymptotic and finite-size regimes.

[1] Q. Liu *et al.*, Entropy 24, 1334 (2022).

[2] F. Grosshans and P. Grangier, Phys. Rev. Lett. 88, 057902 (2002).

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Color centers in Silicon : generation and control of their optical properties

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Researchers and engineers have been exploring ways to integrate light sources in silicon photonics for decades. Recently, fluorescent point defects in Silicon, also known as color centers, have been explored as promising candidates for such light sources in the near-infrared and telecom bands. Moreover, individual defects acting as individual emitters may pave the way towards the integration of quantum photonic devices with existing silicon-based electronic platforms. However, the current processes for creating such defects are complex, commonly requiring one or two implantation steps. In this work, we have demonstrated implantation-free G and W-centers in commercial silicon-on-insulator substrates using femtosecond laser annealing (see Fig. 1a). Furthermore, we have observed that a low-temperature annealing annihilates the G-centers while slightly enhancing the emission of the W-centers. This allows us to generate W-centers in a restricted area of a size close to the cross section of the femtosecond laser spot [1]. A second step is the enhancement of the color center optical properties by coupling them with photonic structures. For exemple, we have found a way to improve G centers emission directivity by embedding them into silicon Mie resonators (see Fig.1 b and c) fabricated by dewetting, achieving an extraction efficiency exceeding 60% with standard numerical apertures. This approach could lead towards ultra-bright telecom band single photon sources in silicon [2].

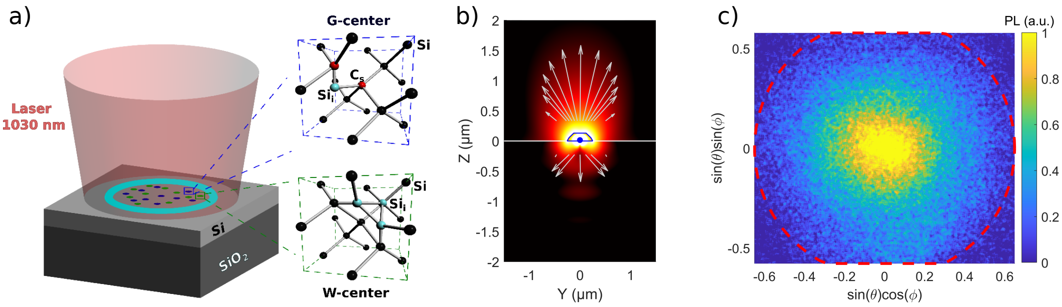

FIG. 1: a) Schematic representation of the femtosecond laser irradiation process used to create G and W-centers. b) FDTD simulation of the Poynting vector of the emission of a dipole representing a color center embedded in a Mie resonator. c) Experimental far-field emission profile of G-centers embedded into Mie resonators obtained by angle-resolved photoluminescence spectroscopy.

[1] H. Quard, M. Khoury, A. Wang, T. Herzig, J. Meijer, S. Pezzagna, S. Cueff, D. Grojo, M. Abbarchi, H.S. Nguyen, N. Chauvin, and T. Wood, "Femtosecond laser induced creation of G and W-centers in silicon-on-insulator substrates", arXiv:2304.03551 (2023).

[2] M. Khoury, H. Quard, T. Herzig, J. Meijer, S. Pezzagna, S. Cueff, M. Abbarchi, H.S. Nguyen, N. Chauvin, and T. Wood, "Light Emitting Si-Based Mie Resonators: Toward a Huygens Source of Quantum Emitters", Adv. Opt. Mat. 10, 2201295 (2022).

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Enabling quantum secured communication over a single fiber, with a single transmitter.

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Quantum key distribution (QKD) has emerged as one of the most advanced and readily available technologies from the second quantum revolution. The so-called Continuous Variable (CV) version of these protocols relies on electromagnetic field quadratures to encode information. It is best suited for integration into metropolitan networks due to its cost-effective implementation, high key rate, and relatively good compatibility with simultaneous transmissions over the same fiber.

In early CVQKD, transmitting the Local Oscillator (LO) alongside the QKD signal caused issues : limited LO power due to channel losses, quantum channel disturbances, and the risk of side-channel attacks, since shot noise calibration depends on LO intensity and security [1].

To address these challenges, a common practice is to have Bob's lab (the receiver) originate the Local Oscillator (LO) instead of Alice's (the sender), avoiding transmission through the untrusted channel. This approach, using a separate laser source for the LO, introduces the phase recovery problem due to differing phase noises and probable frequency offset between the laser sources. Usually, a 'pilot tone' is transmitted alongside the QKD signal using an orthogonal optical mode (e.g., polarization, frequency, time...). It acts as a phase reference, correcting the phase for both classical and CVQKD signals [2].

In our innovative approach, we get rid of these pilot tones, which serve solely as phase references, and transmit a full classical communication channel instead [3]. This channel not only carries classical data but is also used to estimate and correct the phase and frequency differences between the LO and signal lasers.

Since QKD offers information-theoretic security when correctly implemented, One Time Pad (OTP) encryption becomes the natural choice for long-term data protection, ensuring that the encrypted message remains secure indefinitely. Our experiment enables the efficient transmission of both QKD data and the required classical data for post-processing and cryptogram transmission, on different subcarriers.

In our protocol, multiple classical data transmissions are necessary for parameter estimation (from Alice to Bob) and reconciliation (from Bob to Alice for reverse reconciliation). Bob's 'reverse-reconciliation' [4] involves sending classical data to Alice, eliminating the hard $\frac{1}{2}$ channel loss limit that otherwise restricts CVQKD to short distances with 'direct-reconciliation' methods. This can be achieved through a two-way protocol, where Bob also sends both classical and quantum signals that Alice measures. This approach enables us to include the necessary backward transmission in Bob's classical link budget. We then transmit the OTP-encrypted secret message through these classical communication channels, making it decipherable using the key distilled from the previous round.

To maximize secret key rates while ensuring efficient transmission of necessary data and cryptograms, a link budget was estimated and we conducted a thorough experimental analysis of controllable parameters affecting excess noise. This allows us to establish an optimal operating point.

[1] B. Qi, P. Lougovski, R. Pooser, W. Grice, and M. Bobrek, Physical Review X **5**, 041009 (2015), arXiv :1503.00662 [quant-ph].

[2] F. Laudenbach, B. Schrenk, C. Pacher, M. Hentschel, C.-H. F. Fung, F. Karinou, A. Poppe, M. Peev, and H. Hübel, Quantum **3**, 193 (2019), arXiv :1712.10242 [quant-ph].

[3] R. Aymeric, Y. Jaouën, C. Ware, and R. Alléaume, Proc. SPIE Int. Soc. Opt. Eng. **12133**, 22 (2022).

[4] F. Grosshans and P. Grangier, "Reverse reconciliation protocols for quantum cryptography with continuous variables," (2002), arXiv :quant-ph/0204127.

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Towards realistic photonic device-independent quantum key distribution

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Device-independent quantum key distribution (DIQKD) reduces the vulnerability to side-channel attacks of standard QKD protocols by removing the need for characterized quantum devices. The higher security guarantees come however, at the price of a challenging implementation. In this presentation, we tackle the question of the conception of a realistic DIQKD experiment with photonic devices.

First, we set a benchmark by exploring the experimental requirements and limitations of DIQKD based on photons entangled in polarization [1]. Employing DIQKD protocols enhanced by a combination of recent protocols improvements [2–6], we derive bounds on detection efficiency and finite visibility. Additionally, we compute an upper-bound on the key rate using the convex-combination attack, yielding bounds that are protocol-agnostic. Together, these results provide clear benchmarks against which alternative photonic experiment designs can be assessed.

We then introduce a method combining reinforcement learning, optimisation algorithm and a custom efficient simulation of quantum optics experiments to automate the design of photonic setups maximizing a given function of the measurement statistics [8]. Applying our method to DIQKD, we get unexpected experimental configurations leading to high key rates and to a high resistance to loss and noise. These configurations might be helpful to facilitate a first implementation of DIQKD with photonic devices and hold promise for future developments aimed at enhancing performance.

[1] X. Valcarce, C. Lanore, J-D. Bancal, and N. Sangouard, *Device-independent quantum key distribution with polarization entangled photons*, to be published.
[2] M. Ho, P. Sekatski, E. Y.-Z. Tan, et al. *Noisy Preprocessing Facilitates a Photonic Realization of Device-Independent Quantum Key Distribution*, Phys. Rev. Lett. 124, 230502 (2020).
[3] E. Woodhead, A. Acín, and S. Pironio*Device-independent quantum key distribution with asymmetric CHSH inequalities*, Quantum 5, 443 (2021).
[4] P. Brown, H. Fawzi, and O. Fawzi, *Device-independent lower bounds on the conditional von Neumann entropy*, arXiv:2106.13692 (2021)
[5] R. Schwonnek, K.T. Goh, I.W. Primaatmaja, et al. *Device-independent quantum key distribution with random key basis*, Nat Commun 12, 2880 (2021).
[6] E. Y.-Z. Tan, P. Sekatski, J-D. Bancal, et al. *Improved DIQKD protocols with finite-size analysis*, Quantum 6, 880 (2022).
[7] K. Łukanowski, M. Balanzó-Juandó, Máté Farkas, et al. *Upper bounds on key rates in device-independent quantum key distribution based on convex-combination attacks*, arXiv:2206.06245
[8] X. Valcarce, P. Sekatski, E. Gouzien, A. Melnikov, and N. Sangouard, *Automated design of quantum-optical experiments for device-independent quantum key distribution*, Phys. Rev. A 107 (6), 062607 (2023).

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Entanglement source for space and ground quantum communication applications

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Communication security is of central interest in our society and faces new threats with the rise of quantum computers. Therefore, more and more resources are used for the development of highly secured communication protocols. Among those, Quantum Key Distribution (QKD) provides secure key establishment between distant partners, with unconditional security. The past 10 years have seen the near-deployment of several QKD links but for now, fibre based QKD have distance limits because of the losses (0.17 dB/km) and the impossibility of amplifying quantum signals. Thus, the development of hybrid quantum communication networks between ground (fibre networks) and space (satellites) segments is necessary. Several space-compliant sources have been designed, from concepts to demonstrators [1–3]. We have developed a compact and transportable packaged entangled-photon source compatible with existing fibre communication networks, allowing energy-time and polarisation encoding, with the aim of fulfilling spatial constraints in terms of robustness, compactness and integrability.

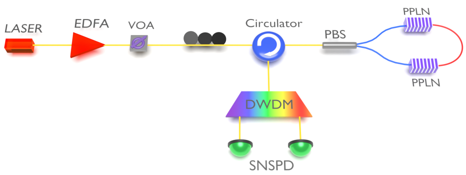

Figure 1. Scheme of the entangled-based sagnac configuration source.

The source design is given in Figure 1 : a telecom continuous-wave laser (at 1560 nm) pumps two pigtailed ridged PPLN:MgO crystal waveguides arranged in a Sagnac loop. The pump laser is converted to visible light (at 780 nm) via second harmonic generation (SHG). Whatever the photon propagation direction in the loop, visible light generated by the first crystal is used as pump to generate degenerate telecom entangled photon pairs in the second crystal via spontaneous parametric down conversion (SPDC). At the output of the loop, the contributions of each path (clockwise and counter clockwise) to the photon-pair state are combined using a polarisation beam splitter leading to a polarisation entangled state $|\phi^+\rangle = \frac{|HH\rangle+|VV\rangle}{\sqrt{2}}$. An optical amplifier combined with a variable optical attenuator allows to control the power sent in the sagnac loop. Filtering steps at both the input and output of the circulator are used to reject both amplified spontaneous emission (ASE) and residual pump at the loop output. Note that energy-time entanglement is naturally generated by the source via SPDC. In addition, the Sagnac configuration allows polarisation entanglement and self-stabilization of the propagating state-contributions in both directions. The spectral width of the generated photons (80 nm at FWHM) allows to exploit DWDM for wavelength multiplexing over 40 standard channels. First results show a CAR of 2000 at the source output and state of the art's entanglement qualities. Energy-time and polarisation entanglements have been qualified using a fiber-folded Franson and a state tomography setup, respectively. For energy-time, two-photon interference fringes have been measured with a raw visibility of 99.98 ± 0.05%. For polarisation, a purity of $99.9 \pm 0.05\%$ and a $99.6 \pm 0.05\%$ fidelity have been obtained, making the source an ideal candidate for QKD applications. Moreover, the source has been integrated to the Quantum@UCA network [4] and we have generated secret keys in both polarisation and energy-time encoding with SKR of 3.5 kbps and 3.8 kbps at 4% QBER, respectively. With this amount of QBER, our source can produce up to 150 Mpair/s for one ITU channel pair. Those results, as well as the design simplicity, compactness, lightness and resilience make this source a good candidate for real-field QKD implementations, including space applications.

[1] E. Beckert *et al*, "A space-suitable, high brilliant entangled photon source for satellite based quantum key distribution", SPIE **10910**, 260-273 (2019).
[2] J. Yin *et al*, "Satellite-based entanglement distribution over 1200 km", Science **356**, 1140-1144 (2017).
[3] Z. Tang *et al*, "Generation and Analysis of Correlated Pairs of Photons aboard a Nanosatellite", Phys. Rev. Applied **5**, 054022 (2016).
[4] Y. Pelet *et al*, "Operational entanglement-based quantum key distribution over 50 km of real-field optical fibres", 2207.14707 (2022).

Poster session 1 (Wed. 22$^{\text{nd}}$): Quantum Processing, Algorithms & Computing (QPAC)

Learning unitaries with quantum statistical queries

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In this work we propose a model for learning unitary operators from quantum statistical queries (QSQs) with respect to their Choi-Jamiolkowski state. Our work is a natural extension of a previous model for learning classical Boolean functions from quantum statistical queries with respect to quantum examples [1, 2]. Quantum statistical queries capture the capabilities of a learner with limited quantum resources, which receives as input only noisy estimates of expected values of measurements. Our methods hinge on a novel technique for estimating the Fourier mass of a unitary on a subset of Pauli strings with a single quantum statistical query, generalizing a previous result for uniform quantum examples. Exploiting this insight, we show that the celebrated quantum Goldreich-Levin algorithm can be implemented with quantum statistical queries, whereas the prior version of the algorithm involves oracle access to the unitary and its inverse [3].

We also show that a wide class of unitaries is efficiently learnable in our model. Particularly, we prove that $\mathcal{O}(\log n)$-juntas [4, 5], quantum Boolean functions with constant total influence [6] and constant-depth circuits are efficiently learnable in our model, while previous algorithms required direct access to the Choi-Jamiolkowski state or oracle access to the unitary and its inverse. Moreover, our upper bounds imply that the actions of those classes of unitaries on locally scrambled ensembles can be efficiently learned.

Despite these positive results, resorting to quantum statistical queries leads to an exponentially larger sample complexity for certain tasks, compared to separable measurements to the Choi-Jamiolkowski state. In particular, we show an exponential lower bound for learning a class of phase-oracle unitaries and a double exponential lower bound for testing unitarity of channels, adapting to our setting previous arguments for quantum states. Finally, we suggest a potential application of our results to hybrid quantum machine learning. Prior work [7, 8] showed that certain quantum learning models can be replaced by classical surrogates during the prediction phase. We argue that the learning algorithms in the present paper can also serve to this scope. To this end, we extend the definition of classical surrogates from the worst-case to the average-case.

[1] Srinivasan Arunachalam, Alex B Grilo, and Henry Yuen. Quantum statistical query learning. *arXiv preprint arXiv :2002.08240*, 2020.

[2] Srinivasan Arunachalam, Vojtech Havlicek, and Louis Schatzki. On the role of entanglement and statistics in learning. *arXiv preprint arXiv :2306.03161*, 2023.

[3] Ashley Montanaro and Tobias J Osborne. Quantum boolean functions. *Chicago Journal OF Theoretical Computer Science*, 1 :1–45, 2010.

[4] Thomas Chen, Shivam Nadimpalli, and Henry Yuen. Testing and learning quantum juntas nearly optimally. In *Proceedings of the 2023 Annual ACM-SIAM Symposium on Discrete Algorithms (SODA)*, pages 1163–1185. SIAM, 2023.

[5] Zongbo Bao and Penghui Yao. Nearly optimal algorithms for testing and learning quantum junta channels. *arXiv preprint arXiv :2305.12097*, 2023.

[6] Cambyse Rouzé, Melchior Wirth, and Haonan Zhang. Quantum talagrand, kkl and friedgut's theorems and the learnability of quantum boolean functions, 2022.

[7] Franz J Schreiber, Jens Eisert, and Johannes Jakob Meyer. Classical surrogates for quantum learning models. *Physical Review Letters*, 131(10) :100803, 2023.

[8] Sofiene Jerbi, Casper Gyurik, Simon C Marshall, Riccardo Molteni, and Vedran Dunjko. Shadows of quantum machine learning. *arXiv preprint arXiv :2306.00061*, 2023.

A noise protected superconducting Fluxonium qubit

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Since its initial demonstration in the early 2000s, there has been a significant improvement in the coherence time of superconducting qubits, with an increase of five orders of magnitude. However, despite this progress, current performances are still insufficient for the development of a versatile quantum processor. Currently, the Fluxonium qubit stands as the circuit with the longest observed coherence, with recent experiments showing it can achieve milliseconds of coherence [1]. It is a superconducting loop made of a Josephson junction shunted by a large inductance (often called a super-inductance). Since the loop is closed, an external magnetic field threading the loop can be used to tune the circuit parameters.

Several groups have implemented a strategy to create a Fluxonium device with a very low frequency of 1-10 MHz. This approach results in a reduced relaxation rate due to the decrease in the charge matrix element at lower frequencies.

In this work, we use the Fluxonium qubit in a new regime. In this regime, the qubit wave functions are de-localized over several potential wells and can be engineered such that the overlap between the ground and excited states is minimal, hence guaranteeing an extremely small matrix element or equivalently a very long relaxation time. Additionally, the qubit transitions offer a very low sensitivity to flux noise thanks to the very large inductance. Coherence times ten times larger than state-of-the-art two-dimensional superconducting qubits are expected for this new type of Fluxonium qubit.

[1] A. Somoroff, Q. Ficheux, R. A. Mencia, H. Xiong, R. Kuzmin, and V. E. Manucharyan, "Millisecond Coherence in a Superconducting Qubit", Phys. Rev. Lett. 130, 267001 (2023).

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Anti-crossings occurrence as exponentially closing gaps in Quantum Annealing

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Quantum annealing (QA) is one of the two promising frameworks for quantum computing that may end with a quantum advantage because it seems well-suited to solve combinatorial optimization problems. It stands for the analog part of the gate-based model (comparable to QAOA). The goal of quantum annealing is to let a quantum system evolve along a trajectory according to the Schrödinger equation. Given some hypotheses, if the Hamiltonians are well defined, measuring the final state after a long enough evolution gives (with high probability) the optimal solution to the optimization problem. This result is guaranteed by the adiabatic theorem. This latter theorem states that, by allowing a runtime inversely proportional to the square of the minimum spectral gap, this ensures a constant probability of observing the optimal solution. In general, exponentially closing minimum gaps yields a running time exponential in the input size but this is only an empirical result.

One major obstacle to this computing model is its analytical analysis, the continuous part of QA makes the equations very difficult to manipulate. Since Wilkinson (1989), a physical phenomenon called avoided level crossing (or anti-crossing AC) is known to create an exponentially closing gap bringing the provable runtime to solve an optimization problem to be exponential in the size of the problem. It is important for the reader to note that there is still no consensus on a formal definition of an AC. Nevertheless, all definitions agree that an AC only occurs in case of an exponentially closing gap. Some authors [1] consider that exponentially small gaps can appear without constituting an AC because in some situations it is unclear that such gaps come from first-order quantum phase transition. In the rest of the paper, we will call AC an exponentially closing gap following the work of [2]. We will moderate this assertion, as well as the computational inefficiency of QA, in the discussion after the numerical study.

In general, studying the instantaneous eigen pairs, and *a fortiori* ACs, is a hard problem since there is no close expression for them. In this work, we use a perturbative expansion of the initial state, the ground state and the first excited state as in [2] to manipulate simpler expressions while still being able to say something about the eigenenergies. This perturbative analysis allows us to derive a condition on the occurrence of an AC during the process. We then apply this condition to the well-known MaxCut problem, a fundamental combinatorial optimization problem that has numerous applications in various fields, including computer science (Pinter problem) and physics (Ising models). We show that on regular bipartite graphs, there is no appearance of AC during the annealing but if we remove the regularity constraint, we can construct a family of bipartite graphs that satisfies the condition of AC's occurrence. The striking outcome is that exponentially closing gaps can arise while solving MaxCut on a bipartite graph if it is irregular enough. To the best of our knowledge, these are the first proven results on MaxCut using QA. To support this theoretical development, we provide numerical analyses of the gaps of small instances, demonstrating the presence of ACs. A final uncommon observation is that QA seems to efficiently solve MaxCut on such instances, despite the presence of exponentially small gaps, thus raising the question of the relation between QA failure and exponential closing gaps.

[1] Boris Altshuler, Hari Krovi, and Jérémie Roland. Anderson localization makes adiabatic quantum optimization fail. *Proceedings of the National Academy of Sciences*, 107(28) :12446–12450, 2010.

[2] Matthias Werner, Artur García-Sáez, and Marta P. Estarellas. Bounding first-order quantum phase transitions in adiabatic quantum computing. *arXiv preprint arXiv :2301.13861*, 1 2023.

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Parametric longitudinal read-out of a semiconductor charge qubit

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Increasing the fidelity and speeding up the read-out of quantum bits has revealed a key challenge in the realm of quantum computing. The read-out of semiconductor qubits traditionnaly relies on the mechanism of dispersive coupling to a microwave resonator [1]. We investigate here a relatively unexplored interaction between a semiconductor charge qubit and a radiofrequency resonator, known as longitudinal coupling [2], which has been recently implemented in the context of superconducting qubits [3, 4]. Such an interaction would allow multiplexed and quicker measurements of multiple qubits while operating a single resonator. Furthermore, the longitudinal coupling commutes with the measured qubit observable offering true quantum non-demolition read-out and free of Purcell decay. Finally , it would allow fast and high-fidelity two-qubit CPHASE gates [5–7].

To engineer this interaction, the qubit has to be driven at the resonator frequency. However, this drive tends to induce an unwanted photon population of the resonator, adding a non-negligible component due to dispersive coupling. We prevent that by applying a rigorous compensation protocol that cancels out photon leakage into the resonator [3].

We study both dispersive and longitudinal qubit-resonator interactions as a function of the qubit Larmor frequency in the adiabatic regime. We report a conditional parametric displacement of the resonator field (see FIG.1.(a)), and rule out any dispersive contribution (see FIG.1.(b)), demonstrating a purely longitudinal interaction between the qubit and the resonator. Our work paves the way to the longitudinal read-out of spin-qubits in semiconducting hybrid devices [8].

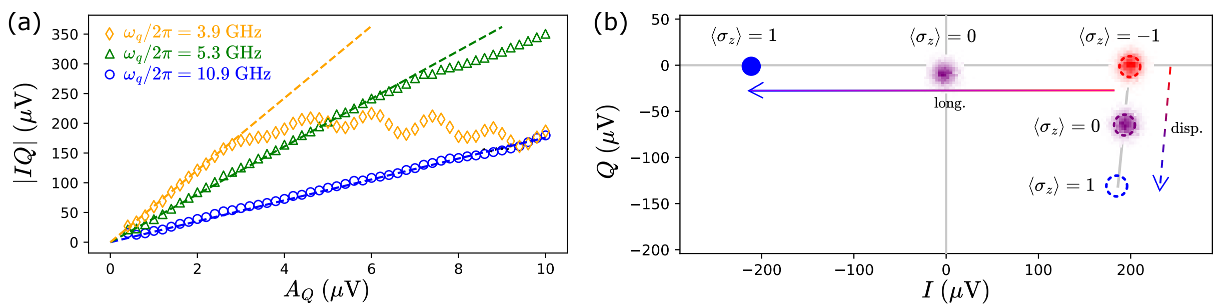

FIG. 1. **(a)** Parametric modulation of the displacement field, represented as amplitude versus power of the drive for different qubit Larmor frequencies ω_q. The slope of the modulation increases with decreasing ω_q as expected, up to a saturation due to Landau-Zener-Stückelberg interferences. **(b)** Cavity field conditional displacement depending on the state of the qubit and on the read-out mechanism.

[1] Vigneau et al., arXiv:2202.10516 (2022)
[2] Didier et al., Phys. Rev. Letters 115, 203601 (2015)
[3] Touzard et al., Phys. Rev. Letters 122, 080502 (2019)
[4] Lledó et al., arXiv:2211.05758 (2022)
[5] Michal et al., Phys. Rev. B 107, 041303 (2023)
[6] Schuetz et al., Phys. Rev. B 99, 241302 (2019)
[7] Harvey et al., Phys. Rev. B 97, 235409 (2018)
[8] Yu et al., Nat. Nano. 18, 741 (2023)

Leveraging 2-photon dissipation for the universal control of a cat qubit

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Bosonic codes offer a promising framework to achieve hardware-efficient quantum error correction (QEC). An example is the cat code, where the logical $|0\rangle$ and $|1\rangle$ are the coherent states $|\pm\alpha\rangle$ of a harmonic mode called the memory [1]. This allows to increase the bit-flip time exponentially in the photon number $|\alpha|^2$ while only affecting the phase-flip time linearly [2]. It has been shown that a cat qubit can be stabilized autonomously by engineering a dissipative process where the memory mode exchanges photons with its environment by pairs. Previous implementations on superconducting circuits relied on an asymmetrically threaded SQUID (ATS) device which required pumping to meet the frequency-matching condition [2]. Recently, we introduced a new design in which the memory mode is coupled to a lossy buffer mode at twice the memory resonance frequency [3]. This autoparametric circuit does not require pumping, and allowed us to reach a strong two-photon dissipation $\kappa_2/2\pi \approx 2\,\mathrm{MHz}$ leading to a $0.3\,\mathrm{s}$ bit-flip time.

We now demonstrate universal control of this autoparametric cat qubit. We realize an arbitrary Z gate by sending a weak displacement drive orthogonal to α, and a holonomic arbitrary X gate inspired by [4].

Finally, we present a method to leverage two-photon dissipation to improve Wigner tomography of the memory by deflating the measured state into the Fock $|0\rangle$, $|1\rangle$ manifold before executing the Ramsey sequence.

[1] Mazyar Mirrahimi et al. "Dynamically protected cat-qubits: a new paradigm for universal quantum computation". New Journal of Physics 16, n° 4 (April 2014).

[2] Raphaël Lescanne et al. "Exponential Suppression of Bit-Flips in a Qubit Encoded in an Oscillator". Nature Physics 16.5 (May 2020).

[3] Antoine Marquet et al. "Autoparametric Resonance Extending the Bit-Flip Time of a Cat Qubit up to 0.3 s". (July 2023).

[4] Victor V. Albert et al. "Holonomic Quantum Control with Continuous Variable Systems". Physical Review Letters 116.14 (Apr. 2016).

* These authors co-supervised the project

Atomic Quantum Computing as a Service

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Quantum computing has potential to solve hard computational problems that are beyond the capabilities of state-of-the-art classical computers. High processing power and enhanced information storage capacity of quantum computers have direct impact on the fields such as finance, science and technology [1]. Therefore, it is important to make quantum computing resources available to a diverse range of users from multiple disciplines. The proposed EquipEx+/PEPR quantique project aQCess - "Atomic Quantum Computing as a Service" will be a public quantum computing platform based on atomic qubits led by the University of Strasbourg as part of a French and international consortium.

Ultracold Rydberg atoms have recently emerged as one of the most attractive physical systems for quantum simulation and digital quantum computing [2]. I will discuss the conception and design of the aQCess platform, detailing our approach to realize hundreds of high quality qubits based on a dual species architecture of potassium and ytterbium atoms. I will also discuss the different ways to encode qubits in long lived Zeeman and metastable excited states and schemes for fast optical addressing and robust gates which suppress noise and crosstalk effects.

aQCess will make quantum computing more accessible to academia and industry on national and international levels. The platform will be a widely used tool for multidisciplinary research and teaching spanning chemistry, materials science, physics, mathematics, and computer science. It will also be open as a training, testing, and development platform for the growing number of start-ups and established companies investing in quantum technologies.

[1] Y. Alexeev et al., Quantum computer systems for scientific discovery, PRX Quantum **2**, 017001 (2021).

[2] M. Morgado et al. Quantum simulation and computing with Rydberg-interacting qubits, AVS Quantum Sci. **3**, 023501 (2021).

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Distributed search on graphs using discrete time quantum walk

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Introduction Spatial search using discrete time quantum walks (DTQW) has already been extensively studied for several lattices and often derives an asymptotic complexity similar to the Grover algorithm (up to a logarithmic factor) [1–3]. In addition, compared to other algorithms, these spatial searches hold all the interesting properties of a DTQW like locality or transition invariance.

In several works, [names] introduced a model of distributed quantum computing based on the Grover search algorithm [4–6]. This model can tackle problems like computing the diameter[5] or finding triangles[6] in a distributed context. However, this model supposes that some global informations are known by every node of the network. This network has a leader, every node knows the size of the network and has a unique id.

By replacing the Grover algorithm in the procedure mentioned above by a spatial search using DTQW, we could relax or even remove these constraints on the network and use a similar procedure for anonymous distributed quantum computing. Seeing that classical anonymous distributed computing often uses random walks or Markovian processes, using DTQW for anonymous distributed quantum computing is natural.

This gives us a motivation to develop a model of searching DTQW on arbitrary graphs, which is the topic of this work. [7]

Contribution In this work, we propose a model of DTQW on arbitrary graphs well suited to solve searching problems. This model puts the amplitudes of the walker onto the edges of the graph and ensures 2-dimensional coin everywhere.

We show numerical evidences that the model we introduce has optimal asymptotic searching complexity of many well known lattices and graphs. We also numerically investigate the behavior of our model on random scale-free graphs. We show the performances and predictability of our model on such graphs.

We also discuss how such a model can be interpreted in a distributed computing framework.

[1] G. Bezerra, P. H. Lugão, and R. Portugal, Physical Review A **103**, 062202 (2021).
[2] M. Roget, S. Guillet, P. Arrighi, and G. Di Molfetta, Physical Review Letters **124**, 180501 (2020).
[3] P. Arrighi, G. Di Molfetta, I. Márquez-Martín, and A. Pérez, Physical Review A **97**, 062111 (2018).
[4] F. L. Gall, H. Nishimura, and A. Rosmanis, arXiv preprint arXiv :1810.10838 (2018).
[5] F. Le Gall and F. Magniez, in *Proceedings of the 2018 ACM Symposium on Principles of Distributed Computing* (2018) pp. 337–346.
[6] T. Izumi, F. L. Gall, and F. Magniez, arXiv preprint arXiv :1908.11488 (2019).
[7] N. Masuda, M. A. Porter, and R. Lambiotte, Physics reports **716**, 1 (2017).

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Poster session 1 (Wed. 22^{nd})
Quantum Simulation (QSIM)

Inhibition of circular Rydberg atoms decay for quantum simulation application

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Quantum physics has led to a better understanding of microscopic systems, providing us many applications and still promising new possibilities. However when it comes to description of many-body systems, the exponential increase of the Hilbert space with the particle number has kept numerical classical simulation of many-body systems out of our reach. The use of quantum simulators could be a way to explore these systems. In fact, by means of quantum analogue simulators, one could map an unknown system to a fully controllable one in order to grasp a better understanding of the first one, like simulation of spin models with trapped ions or superconducting Qbits [1].

Among all the possible platforms for building a quantum simulators, a promising one is based on Rydberg atoms. In fact, they experience extremely strong atom-atom interactions. They already led to beautiful simulation experiments [2][3]. They mostly use low-l atoms with a lifetime of few $100\,\mu\mathrm{s}$. In order to get access to slower dynamics, such as relaxation or thermalisation processes, atomic lifetime needs to be increased. This can be done by means of circular states, which have a much longer lifetime, around $30\,\mathrm{ms}$ for circular state with $n = 50$. Trapping is necessary to keep atoms in place for this duration. More recently, a successful trapping of circular Rydberg atoms has been demonstrated [4].

However time remains a limiting factor and observation of even slower dynamics would require an even longer lifetime. This can be done by inhibition of the main transitions involved in the atomic decay, by means of a simple structure made of two conductive plates parallel to the atomic orbital [5]. A recent study at room temperature has shown a significant increase of the atomic lifetime [6]. Our proposal is to push this idea forward, and build a quantum simulation experiment experiment at cryogenic temperature in order to get rid of black-body-radiation-induced transfers as well [7]. Our work consist in designing and building an experimental setup in order to trap a chain of circular Rydberg atoms inside a capacitor, at a temperature around $0.8\,\mathrm{K}$. With such a system, we expect atomic lifetime to be increased beyond the minute range, enough to be able to observe around 10^5 interaction cycles. The poster presentation will give an overview of planned experiment and its progress.

[1] D. Hangleiter , J. Carolan , KP. Thébault "Analogue quantum simulation : A new instrument for scientific understanding" Springer Nature (2022)

[2] H. Labuhn, D. Barredo, S. Ravets, S. de Léséleuc, T. Macrì, T. Lahaye, and A. Browaeys, "Tunable Two- Dimensional Arrays of Single Rydberg Atoms for Realizing Quantum Ising Models", Nature **534**, 667 (2016).

[3] S. Ebadi, T. T. Wang, H. Levine, A. Keesling, G. Semeghini, A. Omran, D. Bluvstein, R. Samajdar, H. Pichler, W. W. Ho, S. Choi, S. Sachdev, M. Greiner, V. Vuletic, and M. D. Lukin, "Quantum phases of matter on a 256-atom programmable quantum simulator", Nature **595**, 227 (2021).

[4] B. Ravon, P. Méhaignerie, Y. Machu, A. Durán Hernández, M. Favier, J. M. Raimond, M. Brune, and C. Sayrin "Array of Individual Circular Rydberg Atoms Trapped in Optical Tweezers", Phys. Rev. Lett. **131** , 093401 (2023)

[5] D. Kleppner " Inhibited Spontaneous Emission", Phys. Rev. Lett. **47**, 233 (1981)

[6] H. Wu, R. Richaud, J-M. Raimond, M. Brune and S.Gleyzes "Millisecond-lived circular Rydberg atoms in a room-temperature experiment" , Phys. Rev. Lett. **130**, 023202, (2023)

[7] T. L. Nguyen, J. M. Raimond, C. Sayrin, R. Cortiñas, T. Cantat-Moltrecht, F. Assemat, I. Dotsenko, S. Gleyzes, S. Haroche, G. Roux, Th. Jolicoeur, and M. Brune "Towards quantum simulation with circular Rydberg atoms", Phys. Rev. X **8**, 011032, (2018) .

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Error mitigation by virtual distillation : implementation on superconducting quantum computers

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Despite the long lasting quest for a noiseless and scalable universal quantum computer (QC) that could achieve quantum advantage, currently available platforms require the development and improvement of so-called Noisy Intermediate-Scale Quantum Computers (NISQ)[1]. In these devices, qubit operations are subject to noise, which produces errors at a level that remains beyond the scope of fault-tolerant quantum error correction codes. Nevertheless, a wide variety of error mitigation techniques –relying mostly on post-measurement statistical analysis– have emerged over last decade, with the hope of reducing the error levels at least below the threshold for relevant quantum simulation.

In this poster, I will present and discuss various aspects of the implementation of a recently proposed algorithmic error mitigation technique, dubbed virtual distillation[2, 3], on a real, superconducting quantum computer (IBMQ)[4]. Virtual distillation by derangement consists in preparing several copies of the system of interest (or rather, several identical quantum circuits), and making their output 'interfere' using an ancilla qubit and a so-called derangement operator. Provided that the noise acting on the derangement operator can be mitigated, this procedure yields a significant precision improvement on the estimation of an expectation value, which is suitable for quantum simulation. In the context of NISQ, preparing several copies of a system is not prohibitive because typically, relevant quantum computations are performed on a small number of qubits ($\sim$ 10), while available hardware propose up to 127 qubits. In particular, we propose a practical implementation of the method adapted to a linear qubit layout, using advanced recompilation of the derangement operator. We then discuss the effect of noise on the derangement operator, and show that depolarizing noise can be completely removed by zero-noise extrapolation, using an *exact* formula for the error expansion of the result. Finally, we turn to the case of real IBM quantum computers, on which qubit operations are affected by much more complicated noise channels.

[1] J. Preskill, Quantum **2**, 79 (2018).
[2] William J. Huggins et al., Phys. Rev. X **11**, 041036 (2021)
[3] Bálint Koczor Phys. Rev. X **11**, 031057 (2021)
[4] IBM Quantum (2023)

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Universal quantum processors in dipolar spin systems with Walsh functions

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We propose a protocol to realize quantum simulation and computation in spin-exchange interacting systems with long-range interactions. Our approach relies on the local addressing of single spins with external fields parametrized by Walsh functions. This enables a mapping from a class of target Hamiltonians, defined by the graph structure of their interactions, to pulse sequences. We then obtain a recipe to implement arbitrary two-body Hamiltonians and universal quantum circuits. Performance guarantees are provided in terms of bounds on Trotter errors and number of pulses per step. The latter is shown to have a modest scaling with the system size for a wide class of physically relevant models, and it can be reduced further for locally interacting models. The experimental viability of our protocol is emphasized further by *i)* proving how it realizes dynamical decoupling under simple conditions, *ii)* showing its robustness to pulse-induced errors and *iii)* outlining implementation schemes in trapped ions and Rydberg atom arrays. We demonstrate and numerically benchmark our protocol with examples from the dynamical of spin models, quantum error correction and quantum optimization algorithms.

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Poster session 1 (Wed. 22$^{\mathrm{nd}}$): Transverse Engineering & Methods (TEM)

Low noise fiber laser sources for neutral atom based quantum processors

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Continuous wave low-noise high-power lasers sources are key elements for atomic qubit laser manipulation essential for the next generation of quantum computers and simulators. We develop single frequency and low intensity noise laser architectures using novel fiber amplifiers geometries in the infrared. The fibered laser architecture is the only one promising to reach unprecedented levels of power while maintaining low noise and single frequency characteristics in the 1µm for Yb doped, 1.5µm for Er doped and 1.9µm for Tm doped fibers. We study the combination of these IR sources in non linear frequency conversion crystals to extend high power laser operation to the visible and UV ranges. We demonstrated record power at 1013 nm, useful for the Rydberg transition of Rb, and we are currently developing high power sources at 840 nm as well as 634 nm, which are the first step reach 420 and 317nm, used for Rydberg of Rb and Rydberg of Sr respectively.

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Probing spin state coherence in a Mn-doped InGaAs quantum dot via resonance Raman scattering

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The specific optical selection rules of an InGaAs/GaAs QD doped by a single Mn atom [1] (a magnetic dopant) could be exploited to implement a protocol recently proposed for the generation of cluster states with a single hole spin hosted in a QD molecule [2]. Both types of systems exhibit under specific conditions, similar optical selection rules consisting of Λ-like transitions for spin manipulation and cycling transitions for photon emission. On the path towards this challenging objective, we investigate the coherence between different spin states of the magnetic dopant in a self-assembled InGaAs/GaAs QD, using continuous wave (cw) coherent spectroscopy based on resonance Raman scattering (Fig.1a) [3–5]. In spite of a significant inhomogeneous broadening of the optical transitions observed in the sample, Autler-Townes splittings (ATS) are clearly observed by driving two-level transitions far above the saturation regime (Fig.1b). Probing the saturation due to a fix laser with a second scanning laser in a V-like configuration (Fig.1c) reveals ATS or dips (Fig.1d) whose contrast depends on the coherence within the excited spin states. Simulations based on optical Bloch equations enable us to extract the coherence between theses states.

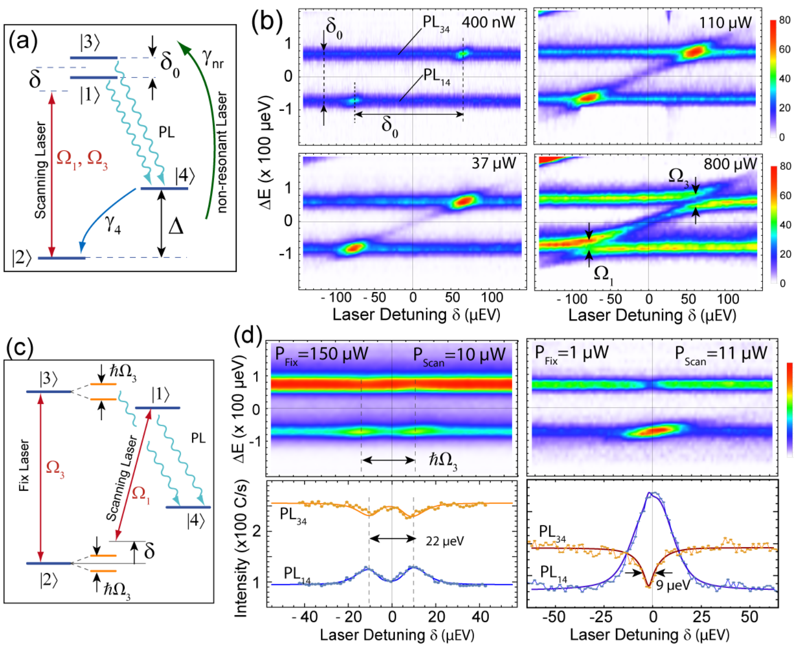

FIGURE 1. (a) Principle of resonance Raman scattering implemented for Mn-doped InGaAs QD. (b) PL intensity spectra of the $|1\rangle \to |4\rangle$ and $|3\rangle \to |4\rangle$ transitions as a function of the laser detuning at different excitation powers. Autler-Townes splitting is spectrally resolved at high power. (c), (d) Saturation spectroscopy to spectrally resolve the Autler-Townes splitting in the low excitation regime and extract spin state coherence.

[1] E. Baudin, et al., Phys. Rev. Lett. 107, 197402 (2011).
[2] A. Vezvaee et al., Phys. Rev. Appl., **18** L061003 (2022).
[3] Xu, X. et al., Science 317, 929 (2007).
[4] D. Chen et al. , Phys. Rev Lett. 118, 037401 (2017).
[5] Vora, P. M. et al., Nat. Commun. 6 :7665, doi : 10.1038/ncomms8665 (2015).

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Hybrid III-V/Silicon photonic sources of entangled photon pairs

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Photonic quantum technologies represent a promising platform for several quantum information (QI) applications: the implementation of integrated devices able to efficiently generate, manipulate and detect quantum states of light is a major objective [1]. Among the available material platforms, silicon stands out as one of the leaders in linear integrated photonics, thanks to its moderate optical losses, large-scale high-yield production capability and fabrication maturity [2]. Although nonlinear effects are accessible through its strong third order susceptibility, it intrinsically lacks of second order nonlinearity; furthermore, its indirect bandgap practically prevents it from achieving laser action. AlGaAs, on the other hand, features both strong second order nonlinearity and direct bandgap, suitable for electrically injected photon-pair production [3], resulting perfectly complementary to silicon for the implementation of a photonic chip for QI applications.

We demonstrate a hybrid AlGaAs/SOI source operating at room temperature, whose working principle is sketched in Figure 1.a: the photon pairs are generated, upon optical pumping, via spontaneous parametric down-conversion (SPDC) in an AlGaAs waveguide based on Bragg reflectors (brown, on top) and then transferred, through evanescent adiabatic coupling, to the SOI circuitry (shades of blue and grey), preserving the properties of the produced quantum state, while the pump beam is automatically filtered out.

Both type 0 and type 2 conversion processes are accessible via SPDC, attesting the versatility of the source. We estimate the amount of photon pairs injected into the silicon waveguides to be $>10^5$ pairs/s in the two cases, with a coincidence-to-accidental ratio (CAR) up to 10^2 (Figure 1.b) over a bandwidth of 90 nm. The non-classicality of the quantum state of light is characterized through an energy-time entanglement measurement, using a fibered Franson interferometer: The obtained visibility is larger than 90% for a 20 nm-broad state (Figure 1.c), demonstrating the high entanglement quality of the produced photons and establishing the potentiality of the proposed hybrid photonic circuit in view of QI applications.

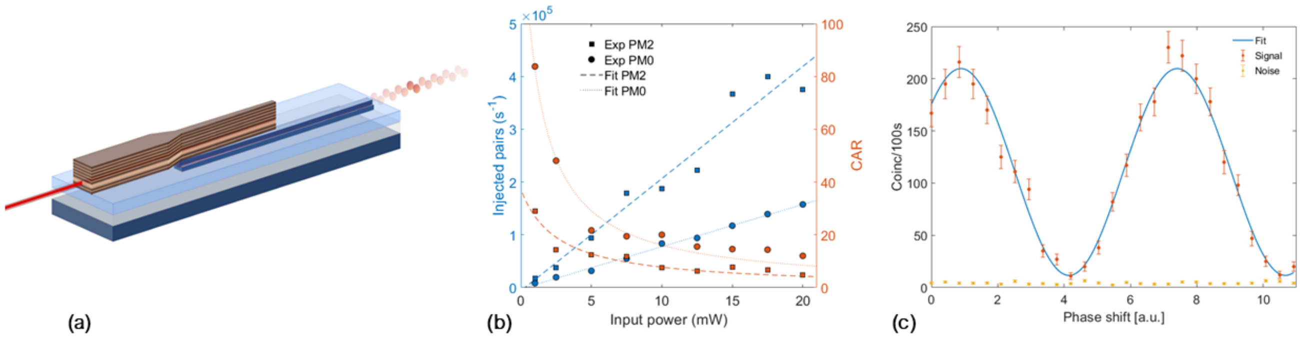

Figure 1. (a) Sketch of the device. Measured (b) injected pairs and CAR, (c) energy-time entanglement visibility.

[1] E. Pelucchi *et al.*, Nat. Rev. Phys. **4**, 194–208 (2022).
[2] S.Y. Siew *et al.*, J. Light. Technol. **39**, 13 (2021).
[3] F. Boitier *et al.*, Phys. Rev. Lett. **112**, 183901 (2014).

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Strain-mediated ion-ion interaction in rare-earth-doped solids

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Atomic ensembles have attracted a lot of attention over the past 20 years due to their inherent capacity to efficiently interact with light. They are at the center of a number of quantum storage protocols. In these light-matter interfaces, the optical depth of the medium is an important figure of merit since it enables high storage and retrieval efficiency. However, reaching large optical depths usually comes with working with large atomic concentrations, leading to reinforced ion-ion interactions and thereby enhanced decoherence. The work reported here addresses the physical mechanisms causing ion-ion interactions in impurity-doped solids, with a specific focus on rare-earth-doped crystals.

It was recently shown that the optical excitation of rare-earth ions produces a local change of the host matrix shape, attributed to a change of the rare-earth ion's electronic orbital geometry [1]. In this work we investigate the consequences of this piezo-orbital backaction and show how it leads to a specific ion-ion interaction mediated by mechanical strain. This interaction, intimately connected to the piezospectroscopic effect, scales as $1/r^3$, similarly to the other archetypal ion-ion interactions, namely electric and magnetic dipole-dipole interactions.

We quantitatively assess and compare the magnitude of these three interactions from the angle of the instantaneous spectral diffusion mechanism, and reexamine the scientific literature in a range of rare-earth doped systems in the light of this generally underestimated contribution [2].

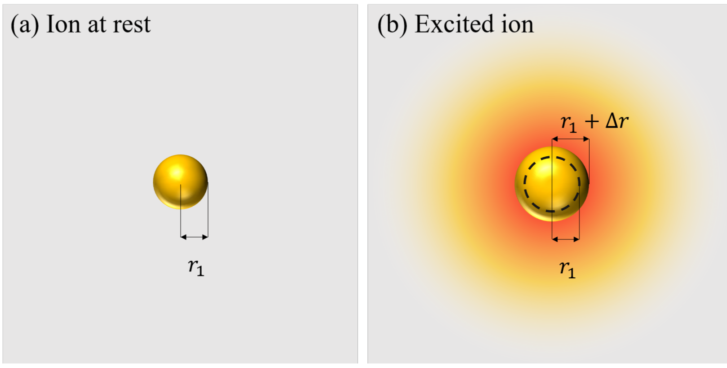

FIGURE 1. Simplified view of the piezo-orbital backaction around a spherical rare-earth ion. The stress field, symbolized by a radial color gradient around the ion, perturbs the surrounding ions via the piezospectroscopic effect.

[1] A. Louchet-Chauvet, P. Verlot, J.-P. Poizat, T. Chanelière, "Piezo-orbital back-action force in rare-earth doped crystals", Physical Review Applied, in production (2023) arXiv :2109.06577.
[2] A. Louchet-Chauvet, T. Chanelière, "Strain-mediated ion-ion interaction in rare-earth-doped solids", Journal of Physics : Condensed Matter **35**, 305501(2023). doi:10.1088/1361-648X/acce17.

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Quantum Optics experiments for (under)graduate students

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For eight years now, we are building a set of quantum optics experiments for our graduate student. These include :

— A now somewhat common Bell's inequality violation setup (Fig. 1a),

but also original experiments :

— single photons having two frequencies thus producing single photons beatnotes [1] (Fig. 1b),
— optimisation of the measurement sequence in the Bell's inequality violation experiment [2] (Fig. 1c),
— polarization state tomography with controlled decoherence [3] (Fig. 2a),

and quite recently :

— single photon interference to introduce experimentally to undergraduate students the quantum physics postulates [4] (Fig. 2b),
— single photons coherence length [4] (Fig. 2c).

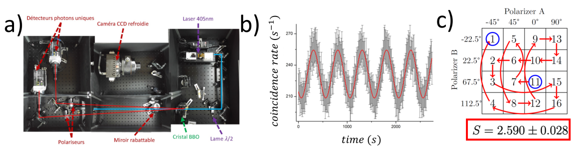

FIGURE 1. a) picture of the experiment b) single photon beatnote c) optimized sequence in a Bell measurement.

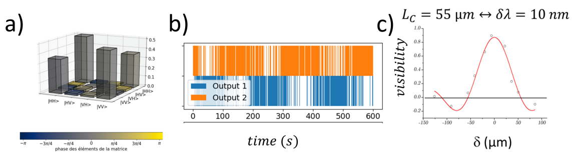

FIGURE 2. a) EPR state tomograpy b) single photon interferences c) single photon coherence length.

[1] Renaud Mathevet, Benoit Chalopin and Sébastien Massenot, Single photon beat note in an acousto-optic modulator-based interferometer, American Journal of Physics 88, 313 (2020).
[2] Alicia Negre, Renaud Mathevet, Benoit Chalopin and Sébastien Massenot, Unexpected optimal measurement protocols in Bell's inequality violation experiments, American Journal of Physics 91, 64 (2023).
[3] internship work of Nicolas Ombredane (M1 @UT3, 2021) and Mélissa Kleine (M2 Photonique Bordeaux, 2022). Unpublished.
[4] To be published.

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Anomalous Conductance Oscillations in the Hybridization Gap of InAs/GaInSb/InAs Triple Quantum Wells

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The quantum spin Hall effect (QSHE) is hosted in a two-dimensional (2D) topological insulator. It consists of an insulating bulk with two helical edge channels protected from back-scattering by time-reversal symmetry. Due to spin orbit coupling the two edge channels are counter-propagating with opposite spins, making the QSHE a perfect candidate for spintronic applications. The QSHE is also envisioned as one of the building blocks for the implantation of topological qubits [1] and for high coherence electronic transport edge channels within flying qubits [2].

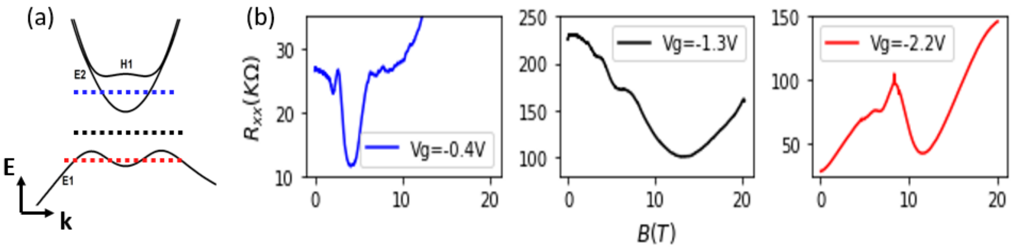

Figure 1. The resistance traces at three gate biases are plotted in (b) to represent the electron ($V_g = -0.4$ V, blue), the hole ($V_g = -2.2V$, red), and the insulating ($V_g = -1.3$ V, black) regimes, respectively. The inverted band structure is schematically plotted in (a), where the Fermi energies of the three curves are labeled.

In this work we investigate InAs/GaInSb/InAs triple quantum wells, predicted to host QSHE with a large topological gap (30 meV). We already measured the energy gap in these structures [3] and found several fingerprints of its topological nature : edge conduction, the presence of two carriers in the valence band and van Hove singularities.Here we search for the theoretically predicted crossing of the zero mode Landau levels in magnetic field. This crossing is detected in several devices by magnetotransport. Moreover, at field B lower than the critical field Bc of the zero-mode crossing, we observe additional oscillations, approximately periodic in 1/B. The temperature dependence of these new oscillations exhibit a combination of thermal activation and smearing effects that defy explanation through conventional theories such as the Lifshitz-Kosevich theory. These oscillations have also been theoretically predicted [4], and recently observed experimentally in broken gap double quantum wells structures based on InAs/GaSb [5]. We will detail how the model proposed in Ref. [5], based on a model Hamiltonian and incorporating a substantial quasiparticle self-energy in the insulating regime, can effectively capture the fundamental characteristics of the observed oscillations within the hybridization gap. Finally, we conclude that these gap oscillations provide further experimental validation of the inverted band structure.

[1] Morteza Aghaee *et al.*, InAs-Al Hybrid Devices Passing The topological Gap Protocol, Phys. Rev. B **107**, 245423 (2023).
[2] C. Bauerle *et al.*, Coherent Control of Single Electrons : a Review of Current Progress, Rep. Prog. Phys. **81**, 056503 (2018).
[3] C.Avogadri *et al.*, Large Inverted Band Gap In Strained Three-Layer InAs/GaInSb Quantum Wells, Phys. Rev. Research **7**, L042042 (2022).
[4] Long Zhang *et al.*, Quantum Oscillation in Narrow-Gap Topological Insulators, Phys. Rev. Lett. **116** , 046404 (2016).
[5] Zhongdong Han *et al.*, Anomalous Conductance Oscillations in The Hybridization Gap of InAs/GaSb Quantum Wells, Phys. Rev. Lett. **123**, 126803 (2019).

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Two-qubit Coupling in the Electron-on-Solid-Neon Platform

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Progress towards the realization of quantum computers requires persistent advances in their constituent building blocks—qubits. Novel qubit platforms that simultaneously embody long coherence, fast operation and large scalability offer compelling advantages in the construction of quantum computers. Electrons, ubiquitous elementary particles of non-zero charge, spin and mass, have commonly been perceived as paradigmatic local quantum information carriers. Despite superior controllability and configurability, their practical performance as qubits through either motional or spin states depends critically on their material environment.

A recent breakthrough was made on electron based qubits with the emergent electron-on-solid-neon (eNe) qubit platform. By trapping single electrons on an ultraclean solid neon surface in vacuum and integrating an electron trap in a circuit quantum electrodynamics architecture, the strong coupling between the motional states of a single electron and a single microwave photon in an on-chip superconducting resonator has been achieved [1]. Superior single-qubit performance has been demonstrated [2]. Both the relaxation time T_1 and coherence time T_2 have reached 0.1-millisecond scale. The observed single-shot readout fidelity, without using a quantum-limited amplifier, is already 98.1%. The average single-qubit fidelity using Clifford-based randomized benchmarking is 99.97%.

Beside single qubit operations, two-qubit gates are required for the universal quantum computing. Here, we show our preliminary results on the two-qubit coupling in this new qubit platform. The microwave photon mediated coupling is demonstrated by the simultaneous strong coupling of two qubits with a common microwave resonator. We also observed the qubit-qubit avoided crossing due to the direct Coulomb (dipole-dipole) interaction.

[1] X. Zhou, G. Koolstra, X. Zhang, G. Yang, X. Han, B. Dizdar, X. Li, R. Divan, W. Guo, K. Murch, D. I. Schuster, and D. Jin, "Single electrons on solid neon as a solid-state qubit platform", Nature **605**, 46-50 (2022).

[2] X. Zhou, X. Li, Q. Chen, G. Koolstra, G. Yang, B. Dizdar, Y. Huang, C. S. Wang, X. Han, X. Zhang, D. I. Schuster and D. Jin, "Electron charge qubit with 0.1 millisecond coherence time", Nature Physics, in production, arXiv:2210.12337 (2023) .

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Poster session 2 (Thu. 23$^{\mathrm{rd}}$): Quantum Sensing & Metrology (QMET)

Monolithic GeSn NW arrays on Si for infrared SPAD detectors

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GeSn semiconductors grown on a Si wafer offer a scalable material platform to engineer a variety of photonic devices (photodetectors, lasers, LEDs) operating in the short-wave infrared (SWIR: 1.5-3 μm) and beyond.[1-3] These GeSn devices are the essential building blocks to develop high-performance infrared sensing and imaging technologies using Si-compatible fabrication processes. The ability to incorporate Sn atoms in Ge at concentrations about one order of magnitude higher than the 1 at.% equilibrium solubility is at the core of these emerging technologies. Importantly, texturing GeSn into NW arrays enhances SWIR optical absorption and results in tunable leaky-mode resonance peaks that are controlled by the NWs geometrical parameters.[4]

In this presentation, we will discuss the structural and optical properties of GeSn NW arrays that are etched from a CVD-grown GeSn p-i-n multi-layer heterostructure. The fabrication of NW-based SAPD detectors will be presented to achieve room temperature operation in the 2 μm band and establish a monolithic platform on Si to extend the capabilities of conventional III-V and II-VI SPAD detectors.

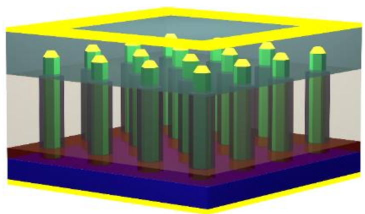

Figure 1 Schematics of the GeSn NW array SPAD detector.

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[1] O. Moutanabbir, et al. Appl. Phys. Lett. **118**, 110502 (2021)
[2] M. Atalla, et al. ACS Phot. **9**, 4 (2022)
[3] L. Luo, et al. ACS Phot. **9**, 3 (2022)
[4] A. Attiaoui, et al. Phys. Rev. Appl. **15**, 014034 (2021)

Realizing an universal electron spin resonance spectrometer using superconducting microwave resonators

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Electron paramagnetic resonance (EPR) is an exquisite tool to analyze and characterize unpaired electrons in a substance. Its wide application in chemistry and pharmaceutical research, biology and physics boosts an active field of research in EPR development. The implementation of superconducting quantum circuits to measure the EPR response has shown [1] to enhance the spin detection sensitivity down to a few spins (≈ 20) on a nanoscale volume (≈ 100 fL) – a gain of five orders of magnitude compared to the state-of-the-art. The unprecedented sensitivity originates from small mode-volume and narrow line-width detection resonators, millikelvin temperatures and amplification of the spin microwave signals using quantum-limit amplifiers. These circuits are however intrinsically characterized by a long ring-down time, making them ill-suited for probing spin species with low coherence times. We propose a dynamical bandwidth tuning of the EPR resonator to lift the constraints on the ring-down time while keeping the benefits offered by superconducting circuits in detection. We are working with Niobium-Titanium-Nitride (NbTiN) alloy[2] and exploiting the kinetic inductance of such magnetic-resilient superconductor to implement the tunability scheme using a varying DC current[3]. This would allow us to perform pulsed-EPR sequences on a large scope of spin species in micron-sized samples adding a tool for new research paths as detection of unpaired electron in single cells or measurement of both inorganic and organic micro-crystal.

[1] Ranjan, V. and Probst, S. and Albanese, B. and Schenkel, T. and Vion, D. and Esteve, D. and Morton, J. J. L. and Bertet, P., "Electron spin resonance spectroscopy with femtoliter detection volume", Applied Physics Letters, 116, 118 (2020)

[2] Samkharadze, N. and Bruno, A. and Scarlino, P. and Zheng, G. and DiVincenzo, D. P. and DiCarlo, L. and Vandersypen, L. M. K.,"High-Kinetic-Inductance Superconducting Nanowire Resonators for Circuit QED in a Magnetic Field",Phys. Rev. Appl.,5,4 (2016)

[3] Bockstiegel, C. and Wang, Y. and Vissers, M. R. and Wei, L. F. and Chaudhuri, S. and Hubmayr, J. and Gao, J., "A tunable coupler for superconducting microwave resonators using a nonlinear kinetic inductance transmission line", Applied Physics Letters 108, 22 (2016).

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Isotopic control of the boron-vacancy spin defect in hexagonal boron nitride

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The negatively-charged boron-vacancy (V_B^-) center in hexagonal boron nitride (hBN) is a promising quantum system for developing spin-based quantum technologies on a two-dimensional (2D) material platform [1]. The electronic spin state of this point defect can be initialized and readout by optical means under ambient condition [2], even in the limit of atomically-thin hBN layers [3], offering interesting prospects for quantum sensing and imaging with unprecedented proximity to the sample being probed [4–6].

In hBN, each site of the honeycomb lattice is occupied by an atom with a non-zero nuclear spin, forming a highly dense nuclear spin environment. Boron has two stable isotopes, ^{11}B ($I = 3/2$, 80% natural abundance (n.a.)) and ^{10}B ($I = 3$, 20% n.a.), while nitrogen occurs either as ^{14}N ($I = 1$, 99.6% n.a.) or ^{15}N ($I = 1/2$, 0.4% n.a.). In hBN crystals with a natural isotopic content, the electron spin resonance (ESR) of V_B^- centers is characterized by a complex seven-line structure resulting from the hyperfine interaction with the three ^{14}N nuclei placed in the first neighboring lattice sites [2]. The hyperfine coupling with the second-neighbors boron atoms rather leads to an overall broadening of each ESR line [7].

In this work, we investigate V_B^- centers in isotopically-engineered hBN crystals. We first show that isotopic purification with ^{15}N yields a simplified and well-resolved hyperfine structure of V_B^- centers, while purification with ^{10}B leads to narrower ESR linewidths [8]. These results establish isotopically-purified h^{10}B^{15}N crystals as the optimal host material for future use of V_B^- spin defects in quantum technologies. We then demonstrate dynamic polarization of ^{15}N nuclei via optical pumping of V_B^- centers in h^{10}B^{15}N. Our analysis indicates that nuclear polarization is mediated by electron-nuclear spin mixing in the ground state of the V_B^- center, with a maximal efficiency of $\sim 30\%$, which is mainly limited by the unequal diagonal components of the hyperfine tensor. These nuclei could be used in future as ancillary quantum memories to enhance the sensitivity of quantum sensors based on V_B^-centers [9] and offer additional ressources for exploring many-body physics in a 2D material platform.

[1] S. Vaidya *et al.*, Advances in Physics : X 8 , 2206049 (2023)
[2] A. Gottscholl *et al.*, Nat. Mater 19, 540–545 (2020)
[3] A. Durand *et al.*, Phys. Rev. Lett. 131, 116902 (2023)
[4] P. Kumar *et al.*, Phys. Rev. Appl. 18 (6), L061002 (2022)
[5] M. Huang *et al.*, Nat. Commun. 13 (1), 5369 (2022)
[6] A. J. Healey *et al.*, Nat. Phys. 11 (1), 87–91 (2023)
[7] A. Haykal *et al.*, Nat. Commun. 13 (1), 4347 (2022)
[8] T. Clua-Provost *et al.*, Phys. Rev. Lett. 131 (12), 126901 (2023)
[9] S. Zaiser *et al.*, Nat. Commun. 7(1), 12279 (2016)

Transmon qubit readout using in-situ bifurcation amplification in the mesoscopic regime

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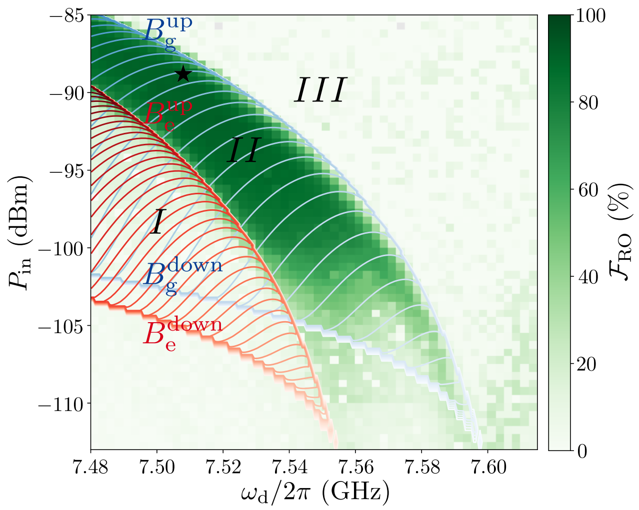
Qubit state readout is a mandatory step in quantum information processing. Here, we demonstrate a transmon qubit readout based on the nonlinear response to a drive of polaritonic meters in-situ coupled to the qubit [1]. Inside a 3D readout cavity, we place a transmon molecule consisting of a transmon qubit and an ancilla mode interacting via non-perturbative cross-Kerr coupling [2]. The cavity couples strongly only to the ancilla mode, leading to hybridized lower and upper polaritonic meters. Both polaritons are anharmonic and dissipative, as they inherit a self-Kerr nonlinearity U from the ancilla and effective decay κ from the open cavity. Via the ancilla, the polariton meters also inherit the non-perturbative cross-Kerr coupling to the qubit. This results in a high qubit-dependent displacement $2\chi > \kappa,\ U$ that can be read out via the cavity without causing Purcell decay. Moreover, the polariton meters, being nonlinear resonators, present bistability, and bifurcation behavior when the probing power increases. In this work, we focus on the bifurcation at low power in the few-photon regime, called the mesoscopic regime, which is accessible when the self-Kerr and decay rates of the polariton meter are similar $U \sim \kappa$. Capitalizing on a latching mechanism by bifurcation, the readout is sensitive to transmon qubit relaxation error only in the first tenths of nanoseconds. We thus report a single-shot fidelity of $98.6\,\%$ while having an integration time of a $500\,\mathrm{ns}$ and no requirement for an external quantum-limited amplifier.



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[1] R. Dassonneville *et al*, "Transmon qubit readout using in-situ bifurcation amplification in the mesoscopic regime", arXiv :2210.04793, accepted at P. R. Applied.

[2] R. Dassonneville *et al*, "Fast High-Fidelity Quantum Nondemolition Qubit Readout via a Nonperturbative Cross-Kerr Coupling", P. R. X **10**, (2020).

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Precision in Hong-Ou-Mandel interferometry : Optimal Scaling and Visibility

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Quantum mechanics provides a profound framework for pushing the boundaries of precision in parameter estimation. One key avenue for exploration is the use of quantum states as probes, with the ultimate precision limit governed by both the intrinsic properties of the state and its dynamics. Time-frequency continuous variables offer a powerful framework for studying light states composed of distinguishable modes populated by individual photons.

In this study, we delve into the interplay between theory and experiment within the context of two-photon Hong-Ou-Mandel interferometry (HOM), shedding light on the limits of precision achievable under realistic conditions.

On one hand, we theoretically investigate the HOM interferometer under ideal conditions (perfect visibility) and derive a general formula for the coincidence probability in a generalized version of the Hong-Ou-Mandel experiment. We systematically analyze the optimality of this measurement setup for arbitrary unitary transformations applied to each input photon, demonstrating that precision limits can be saturated in many ideal situations.

However, achieving this ideal regime in practice remains a challenge. Therefore, we further explore precision limits in two-photon HOM interferometry under realistic circumstances. Remarkably, we identify an optimal scaling regime for precision with visibility, but the ultimate quantum limit remains elusive. These findings shed light on the potential enhancement of precision in quantum measurements and offer valuable insights for practical applications in quantum technologies.

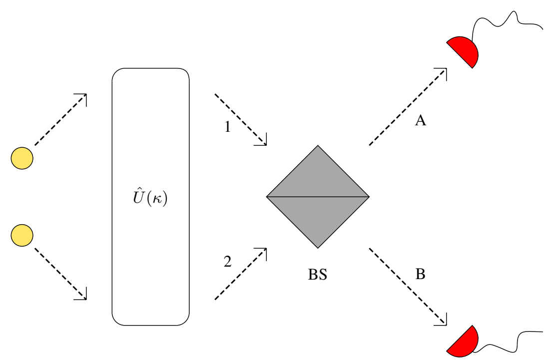

FIGURE 1. Schematics of the HOM inteferometer.

[1] E. Descamps, A. Keller, and P. Milman, Time-frequency metrology with two single-photon states : Phase-space picture and the hong-ou-mandel interferometer, Phys. Rev. A 108, 013707 (2023).

[2] O. Meskine, E. Descamps, A. Keller, A. Lemaître, F. Baboux, S. Ducci, and P. Milman, Fundamental limitations of time measurement precision in Hong-Ou-Mandel interferometry, arXiv :2309.10633 [quant-ph]

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Quantum microscopy of neuronal signals using nitrogen-vacancy centers in diamond nanopillars

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Modern neuroscience has struggled to make advances in diagnosing and treating many neurological disorders due in part to a lack of high-quality means of sensing the electromagnetic signals produced and propagated in neuron networks [1]. We seek to propose a solution to this limitation with the use of the nitrogen-vacancy (NV) center ; an atomic defect in a diamond lattice with unique quantum properties that allows for exceptionally high sensitivity measurements of electromagnetic fields in ambient conditions [2]. Coupling this sensor with the diamond's natural biocompatibility makes the NV an ideal sensor for neuroscience. We place these defects in a diamond nanopillar array which is predicted to create a neuron growth pattern that connects neurons with the nanopillars and circumvents the Debye layer which screens neuron external electromagnetic fields. This technique allows for direct electric field sensing of neuron signals with the NVs. We also detect NV signals with a fast array detector that has a built-in pixel-wise lock-in detection, capable of measurements with submillisecond temporal resolution. Optically conjugating one pillar with one pixel from the camera will obtain ODMR signals for many pillars, allowing for high-sensitivity wide-field imaging with nanoscale spatial resolution.

[1] D. S. Peterka, H. Takahashi, and R. Yuste, "Imaging Voltage in Neurons," Neuron 69(1), 9–21 (2011).

[2] Liam Hanlon, Vini Gautam, James D. A. Wood, Prithvi Reddy, Michael S. J. Barson, Marika Niihori, Alexander R. J. Silalahi, Ben Corry, Jörg Wrachtrup, Matthew J. Sellars, Vincent R. Daria, Patrick Maletinsky, Gregory J. Stuart, Marcus W. Doherty, "Diamond nanopillar arrays for quantum microscopy of neuronal signals," Neurophoton. 7(3) 035002 (6 August 2020) https ://doi.org/10.1117/1.NPh.7.3.035002.

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Pushing further NV-based quantum sensing with photonic sciences

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Quantum sciences are currently being turned into technological devices that have, in regard of their application fields, different degrees of maturity. Diamond Nitrogen-Vacancy (NV) centers, which have proven themselves particularly relevant in the field of quantum sensing, count today as a quite mature technology.

Thanks to a singular interplay between optical and spin degrees of freedom, NV centers have emerged as highly versatile sensors of physical parameters such as magnetic and electric fields, voltage, pressure or again temperature. They have been for example employed to build sensitive magnetometers having an unprecedented nanometric spatial resolution[1]. Together with this versatility, the room temperature operation of NV-based quantum sensors and its solid-state packaging – the diamond – augur further development of a broad range of sensing applications going from biomedical sciences to industrial nondestructive testing.

To fully realize the applicative potential of NV-based quantum sensors, current challenges are to decrease sensors sensitivity down to spin projection noise[2], to miniaturize their size and develop new sensing modalities such as endoscopic or network sensors. Photonic sciences, acting as an enabling technology, represent a clear path to address those challenges. This research direction has been recently started at the "Institut FOTON" with two main lines of research : Integrated photonics with diamond materials and Laser-based techniques for NV spin read-out, which I will present at the GdR TeQ colloquium.

On the topic of integrated photonics, I will outline the contours of a freshly accepted ANR project aiming to develop a sovereign value chain of novel NV-sensors. From the growth of quantum grade diamond layers and their shaping into flat or nanostructured membranes with high NV- center concentration, the project aims to integrate diamond materials onto industrial-grade non-destructive testing fiber-based magnetometers and neuronal electrical activity imaging sensors.

On the topic of laser-based NV spin read-out, I will present research developments building on the concept of Laser Threshold Magnetometry (LTM). In the original LTM proposal[3], the idea is to use NV centers as a laser gain medium allowing to directly use the laser output light as sensing signal. If very high sensitivities are predicted by working close to the laser threshold, building a NV center laser has been found, up to now, to be very challenging. Taking profit from the rich photophysics of diamond NV centers, several strategies have thus been put forward as workarounds. One of them is to use NV centers as an intracavity spin-dependent loss medium in an infrared laser[4]. While this scheme is still waiting for an experimental implementation, further perspectives of using dual-mode lasers or non-linear intra-cavity absorption could allow to reach sensitivities close to the spin projection noise.

[1] Maze et al. "Nanoscale magnetic sensing with an individual electronic spin in diamond", Nature **455**, 644–647 (2008).
[2] Barry et al. "Sensitivity optimization for NV-diamond magnetometry", Rev. Mod. Phys. **92**, 015004 (2020).
[3] Jeske et al. "Laser threshold magnetometry", New J. Phys. **18**, 013015 (2016).
[4] Dumeige et al. "Infrared laser threshold magnetometry with a NV doped diamond intracavity etalon", Opt. Express **27**, 1706-1717 (2019).

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Single shot multiplexed photon number measurement

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It is possible to count the number of photons in a microwave cavity by exploiting the dispersive interaction between a superconducting qubit and the cavity. In standard protocols, it requires to perform a series of gates on the qubit that are conditioned on the cavity occupation, followed by readout operations on the qubit using an ancillary readout resonator [1–3].

Recently, our group introduced a way to realize this counting by multiplexing the driving tones on the qubit and continuously extracting information about the number of photons. A previous experiment managed to show that the counting works on average on many realizations of the experiment and that the coherences between Fock states disappear as expected when the drive is turned on [4].

In this work, we use a new device that is able to resolve the photon number in a single realization of the experiment. The cavity is a high-quality factor 3D superconducting cavity whose lifetime is above 250 μs. A carefully designed filter allows us to drive and measure the emitted field by the qubit at a rate, which is orders of magnitude larger than the decay rate of the cavity. The simultaneous heterodyne detection of the fluorescence field that this qubit emits at all frequencies reveals the photon number in the cavity and produces a quantum backaction on the cavity state. This measurement enables the characterization of the measurement rate of the photon number and of the photocounting fidelity.

Looking forward, we plan to use this experimental platform to first demonstrate high fidelity preparation of Fock states in the cavity, and then their stabilization using continuous measurement-based feedback. Neural networks will be used to train the feedback control.

This work was supported by the QuantERA grant Artemis, by ANR under the grant number ANR-22-QUA1-0004.

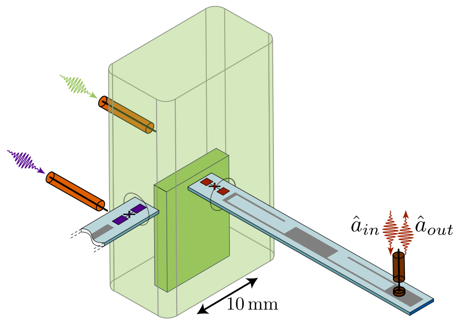

Figure 1 : Scheme of the experiment

[1] B. R. Johnson, M. D. Reed, A. A. Houck, D. I. Schuster, Lev S. Bishop, E. Ginossar, J. M. Gambetta, L. DiCarlo, L. Frunzio, S. M. Girvin et R. J. Schoelkopf : Quantum non-demolition detection of single microwave photons in a circuit. *Nature Physics*, 6(9):663–667, 2010.

[2] Christine Guerlin : *Mesure quantique non destructive repetee de la luniere : etats de Fock et trajectoires quantiques*. Thèse de doctorat, Universite Pierre et Marie Curie - Paris VI, 2007.

[3] R. Dassonneville, R. Assouly, T. Peronnin, P. Rouchon et B. Huard : Number-Resolved Photocounter for Propagating Microwave Mode. *Physical Review Applied*, 14(4):1, 2020.

[4] Antoine Essig, Quentin Ficheux, Théau Peronnin, Nathanaël Cottet, Raphaël Lescanne, Alain Sarlette, Pierre Rouchon, Zaki Leghtas et Benjamin Huard : Multiplexed photon number measurement. *Physical Review X*, 031045:1–33, jan 2020.

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Squeezed light optomechanics with phononic crystals

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Interferometric measurements of mechanical displacements and laser control of mechanical objects are nowadays limited by quantum noises both in gravitational wave interferometers and tabletop optomechanics experiments. These quantum noises are twofold : the Quantum Shot Noise (QSN) related to the laser's phase noise, and the Quantum Radiation Pressure Noise (QRPN) arising from the mechanical response to a fluctuating radiation pressure. Together, they enforce the so called Standard Quantum Limit (SQL). In the mean time, clean room technologies have also reached a point where macroscopic mechanical resonators can be engineered to exhibit quantum behaviours in cryogenic conditions.

Our contribution aims at exploring how frequency dependent squeezed light i.e. squeezed light where the squeezing ellipse angle depends on frequency, can be used to both probe displacements below the SQL on a large frequency range, as well as better controlling the motion of a mechanical resonator.

To this end, a NIR bowtie Optical Parametric Oscillator was built at LKB and a rotation cavity was set up to induce a frequency dependent squeezing angle by detuning it from the carrier field. This very technique has been implemented in advanced gravitational waves interferometers as well [1]. The optomechanical cavity under study is a Membrane At This Edge (MATE) system designed to host a phononic crystal with ultra high Q factor[2][3]. We now have a working OPO and are working towards the rotation/filter cavity optimization as well as a complete characterization of our optomechanical system. Such a quantum limited optomechanical system should be ideally suited for experiments on ground state cooling [4], quantum enhanced metrology[5], and solid state quantum memories [6].

[1] F Acernese et al. (Virgo Collaboration), "Frequency-Dependent Squeezed Vacuum Source for the Advanced Virgo Gravitational-Wave Detector" Phys. Rev. Lett. 131, 041403 (2023)
[2] V. Dumont, S Bernard, C Reinhardt, A Kato, M Ruf, and JC Sankey, "Flexure-tuned membrane-at-the-edge optomechanical system," Opt. Express 27, 25731-25748 (2019)
[3] E Ivanov, T Capelle, M Rosticher, J Palomo, T Briant, PF Cohadon, A Heidmann, T Jacqmin, S Deléglise, "Edge mode engineering for optimal ultracoherent silicon nitride membranes", Appl. Phys. Lett. 117 (25), 254102 (2020)
[4] SA Saarinen, N Kralj, EC Langman, Y Tsaturyan, A Schliesser, "Laser cooling a membrane-in-the-middle system close to the quantum ground state from room temperature," Optica 10, 364-372 (2023)
[5] Y Xia, AR Agrawal, CM Pluchar, AJ Brady, Z Liu, Q Zhuang, DJ Wilson, Z Zhang, "Entanglement-enhanced optomechanical sensing", Nat. Photon. 17, 470–477 (2023)
[6] MB Kristensen, N Kralj, E Langman, A Schliesser, "A Long-lived and Efficient Optomechanical Memory for Light", arXiv :2308.05206 (2023)

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Explicit and efficient estimators for Gaussian state parameters.

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In this study, we employ the method of moments to construct explicit estimators for the parameters characterizing single-mode Gaussian states. Our approach harnesses homodyne data acquired through continuous phase scanning of the local oscillator, enabling efficient parameter estimation. We demonstrate that our estimators reach the Cramer-Rao bound for homodyne measurements, obviating the necessity for computationally intensive methods like maximum likelihood estimation. Hence, this fast estimation of the state parameters can be done during the process of measurement.

The noise of the homodyne measurement of the single-mode Gaussian state can be expressed as

$$A(\psi,\vec{\theta}) = \mathrm{Tr}\left[\hat{X}_\psi^2\,\hat{\rho}(\vec{\theta})\right] = \kappa\left(s\cos^2[\phi_s-\psi] + s^{-1}\sin^2[\phi_s-\psi]\right), \tag{1}$$

where $P = 1/\kappa$ represents the purity of the state, s and ϕ_s correspond to the degree and direction of squeezing, and ψ denotes the phase of the local oscillator. To estimate these three parameters, denoted as $\vec{\theta} = (s,\kappa,\phi_s)$, one can sample the squared quadratures A_j with an oscilloscope for a set of phases ψ_j of the local oscillator. Starting with an initial guess $\vec{\theta}_0$ regarding the parameters of interest, optimal linear combinations Y_k of the measured data can be constructed as

$$Y_k = \frac{1}{N_\psi}\sum_j c_k(\psi_j,\vec{\theta}_0)\,A_j,\ \text{with}\ c_k(\psi_j,\vec{\theta}_0) = \left(\frac{1}{2A^2(\psi_j,\vec{\theta})}\frac{\partial A(\psi_j,\vec{\theta})}{\partial\theta_k}\right)\Big|_{\vec{\theta}=\vec{\theta}_0}. \tag{2}$$

From these linear combinations, one can estimate the parameters as

$$\left(\tilde{s},\tilde{\kappa},\tilde{\phi}_s\right) = \left(\sqrt{\left|\frac{Y_1 s_0(1+s_0)+Y_2\kappa_0}{Y_1(1+s_0)-Y_2\kappa_0}\right|}, 2\kappa_0\sqrt{\left|\frac{Y_1 s_0(1+s_0)+Y_2\kappa_0}{(Y_1(1+s_0)-Y_2\kappa_0)^{-1}}\right|}, \phi_{s0} - \frac{Y_3}{Y_1(1-s_0^2)}\right). \tag{3}$$

This procedure can be iteratively repeated multiple times, updating the initial guess $\vec{\theta}_0$. This approach eliminates the necessity for any prior information about the parameters. The method of moments not only yields estimators but also provides their respective variances. We analytically demonstrate that the accuracy of these estimators reaches the Cramer-Rao bound. Figure 1 showcases the results of the simulated data processing.

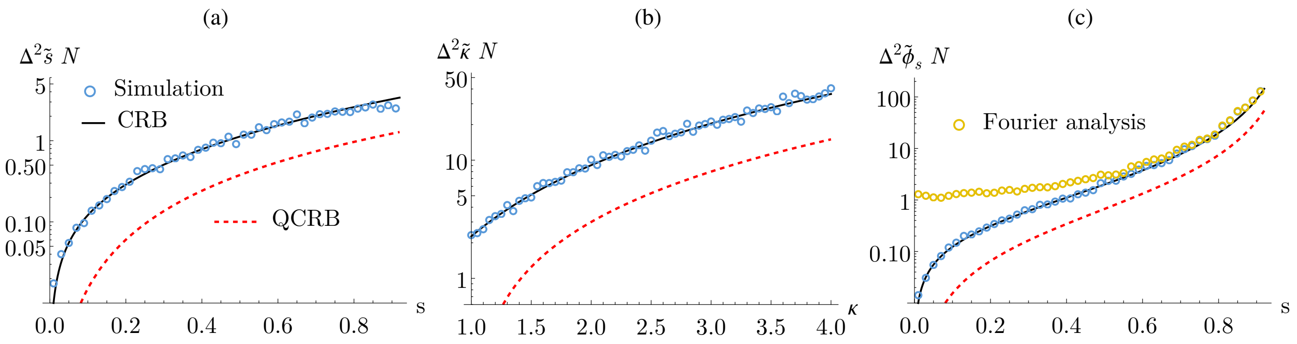

FIGURE 1. Square error of the estimators for the parameters s (a), κ (b) and ϕ_s (c). Points correspond to the square error of the simulated data reconstruction (reconstructed 500 data samples with $N = 1000$, $s = 0.6$, $\kappa = 1.4$, $\phi_s = 0.4$, unless another value is given on the plot axes). Black lines correspond to the Cramer-Rao bound, dashed red line to the quantum Cramer-Rao bound.

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Boron-vacancy spin defects in hexagonal boron nitride under high pressure

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Spin defects with optically detectable magnetic resonances in hexagonal boron nitride (hBN) are currently attracting a deep scientific interest for the deployment of quantum sensing technologies on a two-dimensional (2D) material platform [1]. Among several optically active spin defects recently discovered in hBN, the negatively-charged boron vacancy (V_B^-) centre stands out due to its well-established atomic structure and ease of creation by various irradiation methods [2, 3]. This defect features a spin triplet ground state whose electron spin resonance (ESR) frequencies can be interrogated by optical means even in the limit of atomically-thin hBN layers [4], and strongly depends on external perturbations such as magnetic and electric fields, strain, and temperature [5, 6]. Such properties make the V_B^- center in hBN a promising candidate for the design of a flexible 2D quantum sensing unit, which could offer an ultimate atomic-scale proximity between the spin-based sensor and the probed sample.

Recent proof-of-concept experiments have shown that ensembles of V_B^- centers can be integrated into van der Waals heterostructures and used to image the magnetic field produced by 2D ferromagnets [7–9]. Interestingly, the properties of these materials can be tuned by applying hydrostatic pressure. As an example, the magnetic order of CrI_3 switches from an antiferromagnetic interlayer coupling to a ferromagnetic interlayer coupling for a pressure in the range of few GPa [10, 11]. In this work, we study the optical and spin properties of V_B^- centers in hBN under high pressure in order to assess their potential for magnetic imaging of pressure-induced phase transitions of 2D magnets. To this end, a bulk hBN crystal doped with V_B^- centers is loaded inside a diamond anvil cell (DAC), which is the most widely used device for obtaining hydrostatic pressures above few GPa. Our measurements reveal that the photoluminescence (PL) signal of the V_B^- centers decreases rapidly with pressure and becomes fully quenched near 7 GPa. Time-resolved PL measurements suggest that this effect results from an increase of non-radiative decay channels during optical cycles under high pressure. Despite this pressure-induced quenching effect, we show that the ESR frequencies of V_B^- centers remain optically detectable for hydrostatic pressures up to 3 GPa, without variations of the longitudinal spin relaxation time T_1. These results establish that V_B^- centers can be employed in future to image pressure-induced phase transitions of 2D magnets if they occur in the GPa range. More generally, our work will enable to identify potential applications of V_B^- center in high pressure physics.

[1] S. Vaidya, et al., Adv. Phys : X 8, 2206049 (2023).
[2] A. Gottscholl, et al., Nat. Mater., 19, 540 (2020).
[3] A. Haykal, et al., Nat. Commun. 13, 4347 (2022).
[4] A. Durand, et al., Phys. Rev. Lett. 131, 116902 (2023).
[5] A. Gottscholl, et al., Nat. Commun. 12, 4480 (2021).
[6] P. Udvarhelyi, et al., npj Comp. Mater. 9, 150 (2023)
[7] P. Kumar, et al., Phys. Rev. Applied 18, L061002 (2022).
[8] M. Huang et al., Nat. Commun. 13, 5368 (2022).
[9] A. J. Healey et al., Nat. Phys. 19, 87 (2023).
[10] T. Li, et al., Nat. Mater. 18, 1303 (2019).
[11] T. Song, et al., Nat. Mater. 18, 1298 (2019).

Experimental demonstration of time measurement precision limitations in Hong-Ou-Mandel interferometry

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In quantum mechanics, the precision achieved in parameter estimation using a quantum state as a probe is determined by the measurement strategy employed. The quantum precision limit, a fundamental boundary, is defined by the intrinsic characteristics of the state and its dynamics. Theoretical results have revealed that in interference measurements with two possible outcomes, like the Hong-Ou-Mandel interference, this limit can be reached under ideal conditions of perfect visibility and zero losses [1]. However, in practice, this cannot be achieved, so precision *never* reaches the quantum limit. But how do experimental setups approach precision limits under realistic circumstances? In this work we provide a general model for precision limits in two-photon Hong-Ou-Mandel interferometry for non-perfect visibility and validate it experimentally using different quantum states, including sinc, Gaussian, rectangular and Schrödinger cat-like states [2]. These states are obtained by spectrally filtering the biphoton state generated by an AlGaAs Bragg-reflection waveguide [3]. Our experimental configuration allows us to manipulate and achieve visibility levels of up to 99.4% (see Fig 1.a)). We show that the scaling of precision with visibility depends on the effective area in time-frequency phase space occupied by the state used as a probe. We reveal the existence of an optimal scenario, where we observe a remarkable ratio of 0.97 between the experimental precision $\widetilde{F}_V$ (given by the Fisher information) and the quantum limit $\mathcal{F}$, establishing a new benchmark in the field (Fig 1.b).

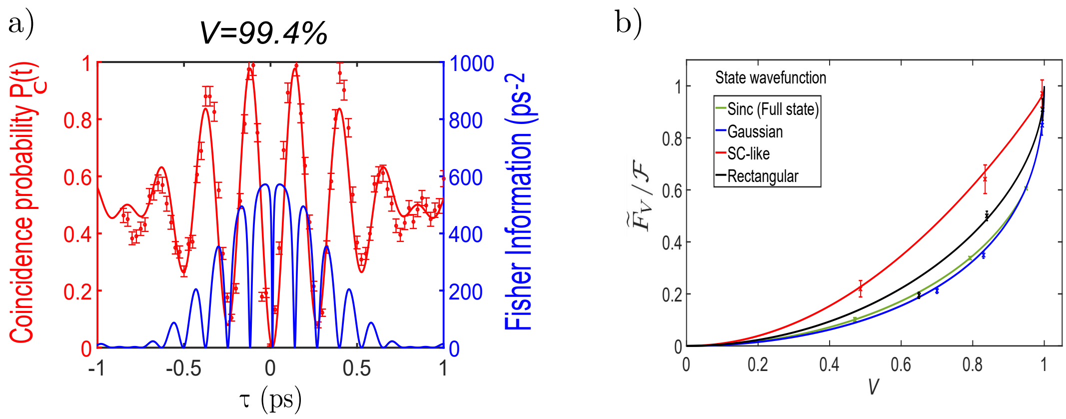

FIGURE 1. a) HOM coincidence probability and Fisher information for a Schrodinger cat-like state b) : Scaling of the ratio $\widetilde{F}_V/\mathcal{F}$ for different states with respect to the HOM visibility V.

[1] E.Descamps et al, "Time-frequency metrology with two single-photon states : Phase-space picture and the Hong-Ou-Mandel interferometer" , PRA 108,013707 (2023)
[2] O.Meskine et al. "Fundamental limitations of time measurement precision in Hong-Ou-Mandel interferometry" arXiv : 2309.10633 (2023)
[3] F.Appas et al, "Nonlinear Quantum Photonics With AlGaAs Bragg-Reflection Waveguides" Journal of Lightwave Technology (2022)

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Gas Detection via Quantum Fourier Transform Infrared Spectroscopy in Long-Path Absorption

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Over recent years, the detection of organic compounds has arisen as a cornerstone for security, health, environmental and pollution issues. The ability to measure low concentrations of gases such as methane, methanol, or nitrogenous compounds, allows to perform tasks such as practical medical diagnoses, explosives detection, or the prevention of pollution from various sources, including industry and agriculture. The Laser technology has enabled the detection of such compounds thanks in particular to Fourier Transform Infrared (FTIR) spectroscopy. The mid-infrared part of the electromagnetic spectrum is of particular interest, for it features molecular transitions involving vibrational and rotational levels, specific to each molecules. However, in order to span this part of the spectrum, conventional FTIR spectrometers rely on noisy and low-efficiency detectors, which also require cooling to operate properly. Applications of FTIR spectroscopy in the mid-infrared region are therefore limited for the time being, particularly in terms of spectral resolution at low gas concentrations.

More recently, the growing interest for induced coherence in quantum photonic interference has opened perspectives for more practical and sensitive FTIR spectrometers in the mid-infrared region. This phenomenon was first introduced by Zou *et al.* in 1991, and involves an interference on the idler photon from a pair emitted via spontaneous parametric down-conversion (SPDC). Remarkably, the visibility of this interference depends on the transmissivity of an optical element placed in the signal photon's path, element that never interacted with the idler photon. Applications of this phenomenon to infrared spectroscopy were only proposed during the last decade [2], with first applications to FTIR spectroscopy proposed by Paterova *et al.* in 2018 [3] and Lindner *et al.* in 2021 [4], who combined induced coherence in a nonlinear Michelson interferometer with Fourier Transform spectroscopy techniques. This allowed them to measure the absorption spectrum of gases in the mid-infrared region, by detecting a near-infrared photon with less noisy, more efficient, and cheaper detectors. These experiments pioneered the field of quantum FTIR spectroscopy, feeding the hope for more sensitive detection of organic compounds in the mid-infrared spectrum.

In this work, we built a quantum FTIR spectrometer displaying the highest sensitivity ever achieved. In order to reach this sensitivity, we built such a nonlinear Michelson interferometer, with enhanced stability allowing to probe the gas in $1.7\,\mathrm{m}$-long interferometer arms. The resulting total absorption consequently increases by two orders of magnitude compared to the most recent experiment of Lindner *et al.* [4]. In addition, we used new post-processing techniques, by filtering out the noise in the spectrum reconstructed via Fourier transform, in a more selective way than the more usual apodization post-processing. This allowed us to resolve faint absorption lines of gases that would otherwise be imperceptible. The resulting sensitivity was high enough to detect the absorption spectrum of ethanol and methanol vapors in ambient air, as well as absorption lines of methane and water vapour from human breath and earth atmosphere. In addition, thanks to the large spectral band allowed by FTIR spectroscopy, multiple gas were identified from the same sample. This way, we showed that quantum FTIR spectroscopy can indeed be used for practical applications, such as medical breath analysis and on-filed gas detection.

[1] X.Y. Zou, L.J. Wang, and L. Mandel, "Induced Coherence and Indistinguishability in Optical Interference", Physical Review Letters, **67** (3), 318 – 321 (1991).

[2] D.A. Kalashnikov, A.V. Paterova, S.P. Kulik, L.A. Krivitsky, " Infrared spectroscopy with visible light", Nature Photonics **10**, 98-101 (2016).

[3] A. Paterova, H. Yang, C. An, D. Kalashnikov, and L. Krivitsky, "Measurement of infrared optical constants with visible photons", New Journal of Physics, **20**, 043015 (2018).

[4] C. Lindner, J. Kunz, S.J. Herr, S. Wolf, J. Kießling, and F. Kühnemann, "Nonlinear interferometer for Fourier-transform mid-infrared gas spectroscopy using near-infrared detection", Optics Express, **29** (3), 4035 - 4047 (2021).

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Scanning NV-center magnetometry for imaging 2D Van der Waals magnets at the nanoscale

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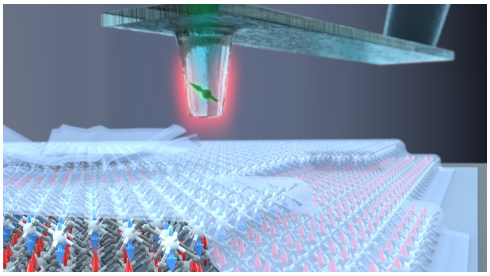
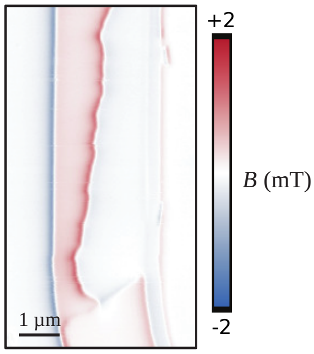
The recent discovery of long-range magnetic order in atomically thin “van der Waals” crystals [1] has attracted significant attention due to its fundamental interest and technological potential. 2D magnetic systems are expected to host exotic spin textures and magnetic phases, however, the observation of magnetic order at the nanoscale, down to a few atomic layers, is out of the reach of most conventional magnetometers.

The Nitrogen Vacancy (NV) center in diamond has become over the past two decades one of the most used solid state spin qubit, thanks to its long coherence time, and the possibility to polarize and read-out its spin state optically at room temperature. The NV-center spin qubit has also proven to be a remarkable atomic-scale magnetometer. In particular, NV center scanning probe - where a single NV center is implanted at the apex of an AFM tip - take advantage of the high sensitivity of the NV center, as well as the extreme spatial resolution offered by an atomic defect.

Scanning NV magnetometry has proven to be a tool of choice for imaging the magnetic structure of 2D crystals [2] : unlike most other nanoscale magnetometers, scanning NV is non-invasive, offers a spatial resolution limited by the sample-to-spin distance of a few 10s of nm, and DC field sensitivity in the $\mu\mathrm{T}/\sqrt{\mathrm{Hz}}$ range.

Our team has recently studied the formation of both ferromagnetic and anti-ferromagnetic domains in bilayers of the wan der Waals magnet CrSBr [3]. We are currently working on the observation of more complex magnetic structures and spin waves in 2D materials.





Left : sketch of a scanning NV probe.
Right : stray magnetic field from a Ferromagnetic/Antiferromagnetic domain wall on bilayer CrSBr

[1] Huang B. et al, "Layer-dependent ferromagnetism in a van der Waals crystal down to the monolayer limit", Nature **546**, 270-273 (2023).
[2] Thiel L. et al., "Probing magnetism in 2D materials at the nanoscale with single-spin microscopy", Science **364**, 973-976 (2019).
[3] Tschudin M. et al, to be published

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Experimental separation estimation of incoherent optical sources at the Cramér-Rao bound

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Resolving light sources below the diffraction limit is a fundamental task both for astronomy and microscopy. Several recent works analysed this problem through the lens of quantum parameter estimation theory and proved that the separation between two point sources can be estimated at the quantum limit using intensity measurements after spatial-mode demultiplexing. We implement this technique and provide an optimal estimator based on a linear combination of demultiplexed intensity measurements [1–3]. Our experimental setup allows for the generation of the images of two sources, with tunable mutual coherence, as well as for spatial mode demultiplexing to estimate their separation [4].

We are able to estimate the separation between two incoherent sources with very good sensitivity in two regimes, at high photon flux (600µW) and at low photon flux (50fW), and are able to saturate the Cramér-Rao bound in both cases.

In the high flux regime, we reach a sensitivity of $3 \times 10^{-5} w_0$, where $w_0 = 1$mm is the waist of the beam, with a 5ms-integration time. This corresponds to an improvement of five orders of magnitude compared to the Rayleigh limit. In the low flux regime, we demonstrate a 30µm-sensitivity, for a 0.1s-integration time, which is slightly above the Cramér-Rao bound, taking into account the noise sources of the experiment (crosstalk, dark counts, shot noise). Preliminary analysis shows that this gap is due to some extra noise in the laser source.

To summarize, we experimentally implement spatial-mode demultiplexing associated with intensity measurements in order to estimate the transverse separation between two incoherent optical sources. This technique allows to saturate the Cramér-Rao bound while taking into account all noise sources (crosstalk, electronic noise) [5].

[1] G. Sorelli, M. Gessner, M. Walschaers, and N. Treps *Optimal Observables and Estimators for Practical Superresolution Imaging*, Phys. Rev. Lett. **127**, 123604 (2021).
[2] G. Sorelli, M. Gessner, M. Walschaers, and N. Treps *Moment-based superresolution : Formalism and applications*, Phys. Rev. A **104**, 033515 (2021).
[3] M. Gessner, C. Fabre, and N. Treps *Superresolution Limits from Measurement Crosstalk*, Phys. Rev. Lett. **125**, 100501 (2020).
[4] P. Boucher, C. Fabre, G. Labroille, and N. Treps *Spatial optical mode demultiplexing as a practical tool for optimal transverse distance estimation*, Optica **7**, 11 1621 (2020).
[5] C. Rouvière, D. Barral, A. Grateau, I. Karuseichyk, G. Sorelli, M. Walschaers, and N. Treps *Ultra-sensitive separation estimation of optical sources*, arXiv preprint arXiv :2306.11916 (2023).

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Scanning-probe thermal imaging based on NV centers

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Lately, a strong effort has been devoted to develop experimental techniques able to measure temperatures at nanometer scales. This effort is motivated by many applications in various domains including biology, chemistry, microfluidics, physics, and micro-electronics. These techniques require fast and quantitative thermal imaging with sub $K/\sqrt{Hz}$ sensitivity and sub-micron spatial resolution under ambient conditions.

To realize this we propose to use nitrogen-vacancy centers in diamonds. These defects possess an electronic spin resonance that can be detected optically [1] and are strongly sensitive to various external perturbations in its environment. As a result, very sensitive quantum sensors based on NV centers have been implemented, capable of locally probing magnetic, electric fields and strain. The sensing capabilities of the NV center can also been extended to thermometry, relying on the shift of the zero-field splitting parameter with temperature [3]. In order to obtain a thermometer based an NV centers with spatial resolution in the nanometer scale and create temperature maps, a diamond atomic force microscope tip hosting several NV centers was optimized by our team and fabricated by QNAMI company. These tips are made with a small volume of diamond to reduce the effect of the large thermal conductivity of diamond which could damp any temperature variation [3]. We expect their optimal thermal sensitivity to be around 1 $K/\sqrt{Hz}$.

In this work, I study several thermometry tips and determine their thermal sensitivity and their spin properties. In particular, I measure three characteristic times noted T_1, T_2^* and T_2. The longitudinal relaxation time T_1 correspond to the time needed to reach thermodynamic equilibrium from a polized state. T_2^* and T_2 characterise the decoherence of a quantum system. These measurements give us insight about the quality of our diamond probes and the reproducibility of their fabrication process.

[1] A Gruber, A Drabenstedt, C Tietz, L Fleury, J Wrachtrup, and C von Borczyskowski. Scanning confocal optical microscopy and magnetic resonance on single defect centers. **Science**, 276(5321) :2012– 2014, 1997.

[2] ictor M Acosta, Erik Bauch, Micah P Ledbetter, Amir Waxman, L-S Bouchard, and Dmitry Budker. Temperature dependence of the nitrogen-vacancy magnetic resonance in diamond. **Physical Review Letters**, 104(7) :070801, 2010.

[3] Rana Tanos, W Akhtar, Serge Monneret, F Favaro de Oliveira, G Seniutinas, M Munsch, P Maletinsky, L Le Gratiet, I Sagnes, A Dr ´eau, et al. Optimal architecture for diamond-based wide-field thermal imaging. **AIP Advances**, 10(2) :025027, 2020.

Poster session 2 (Thu. 23$^{\mathrm{rd}}$): Fundamental Quantum Aspects (FQA)

Thermodynamic analysis of a measurement-free fault-tolerant bit-flip error memory

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Quantum computation needs error correction, to get rid of the noise that appears in the qubits. This process produces entropy, and therefore induces a dissipation of energy. To better understand what would be the energy consumption of a quantum computer, one needs to perform a thermodynamic analysis of the error correction process. To do so, it is interesting to study the entropy flow in an error correction code, and look for an additional theoretical limit to the entropy production, than the Landauer limit. We are studying this in the simplest fault-tolerant error correction code, that only corrects bit-flip errors. For that, we designed a measurement-free fault-tolerant version of the bit-flip quantum memory, and we have started to analyse entropy flows within it.

[1] Landi, G. T., de Oliveira, A. L. F., Buksman, E. (2020). Thermodynamic analysis of quantum error-correcting engines. Physical Review A, 101(4), 042106.

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Giant Quantum Electrodynamic Effects on Single SiV Color Centers in Nanosized diamonds

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Abstract

Understanding and mastering quantum electrodynamics phenomena is essential to the development of quantum nanophotonics applications. While tailoring of the local vacuum field has been widely used to tune the luminescence rate and directionality of a quantum emitter, its impact on their transition energies is barely investigated and exploited. Fluorescent defects in nano-sized diamonds constitute a unique nanophotonic platform to investigate the Lamb shift of an emitter embedded in a dielectric nanostructure with high refractive index. Using spectral and time-resolved optical spectroscopy of single SiV defects, blue shifts (up to 80 meV) of their emission lines were observed, which are interpreted from model calculations as giant Lamb shifts. The observation of spectral position shift of single SiV luminescence upon monitoring the external refractive index, provides an experimental validation of this interpretation. Moreover, experimental evidence for a positive correlation between their fluorescence decay rates and emission linewidths is found, as a signature of modifications not only of the photonic local density of states but also of the phononic one, as the nanodiamond size is decreased. Correlative light-electron microscopy of single SiVs and their host nanodiamonds further supports these findings. These results make nanodiamond-SiVs promising as optically driven spin qubits and quantum light sources tunable through nanoscale tailoring of vacuum-field fluctuations.

Quantum information and sensing with structured light

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The ability to tailor the structure of light is a very powerful concept in modern optics, spanning both the classical and the quantum regime. Vectorial modes of light, a type of structured light where the polarization varies across the beam profile, are a useful tool in quantum information since they provide large alphabets, rich entanglement structures and enhanced resilience to noise. In quantum communication, for instance, vectorial modes enable rotational invariant protocols, therefore overcoming the requirement of a shared reference frame between users [1, 2]. Moreover, structured light can be a resource for enhanced sensing purposes as for instance in the "photonic gears" technique [3]. This scheme enables a boost of sensitivity in mechanical displacements measurement thanks to a bidirectional mapping between the polarization state and a properly tailored vectorial mode of a paraxial light beam. By exploiting this technique, we recently measured, in ordinary ambient conditions, the relative shift between two objects with a resolution of 400 pm [4]. Thanks to a single-optical-path scheme, photonic gears are intrinsically stable and could be implemented as a compact sensor, using cost effective integrated optics.

Quantum interference, on the other hand, is a central resource in many quantum-enhanced tasks, from computation to communication protocols [5]. While it usually occurs between identical input photons, quantum interference can be enabled by projecting the quantum state onto ambiguous properties that render the photons indistinguishable, a process known as a quantum erasing. By combining the concepts of quantum interference and structured light, we recently designed and experimentally demonstrated a simple and robust scheme that tailors quantum interference to engineer photonic states with spatially structured coalescence along the transverse profile [6]. This is done by locally tuning the distinguishability of a photon pair via spatial structuring of their polarization, creating a structured quantum eraser. By combining the potential benefits of photonic coalescence and structured light, we believe these spatially-engineered multi-photon quantum states may be of significance in fields such as quantum metrology, microscopy, and quantum information.

[1] V. D'Ambrosio, et al "Complete experimental toolbox for alignment-free quantum communication", Nat. Comm. **3**, 961 (2012).

[2] V. Parigi, V. D'Ambrosio, C. Arnold, L. Marrucci, F. Sciarrino and J. Laurat "Storage and retrieval of vector beams of light in a multiple-degree-of-freedom quantum memory", Nat. Comm. **6**, 7706 (2015).

[3] V. D'Ambrosio, et al "Photonic polarization gears for ultra-sensitive angular measurements", Nat. Comm. **4**, 2432 (2013).

[4] R. Barboza, A. Babazadeh, L. Marrucci, F. Cardano, C. de Lisio and V. D'Ambrosio "Ultra-sensitive measurement of transverse displacements with linear photonic gears", Nat. Comm. **13**, 1080 (2022).

[5] F. Bouchard, et al "Two-photon interference : the Hong Ou Mandel effect", Rep. Prog. Phys. **84**, 012402 (2020).

[6] C. Schiano, et al "Engineering quantum states from a spatially structured quantum eraser", arXiv :2306.13821 (2023).

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Device Independent Certifications of Indefinite Causal Orders

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For both quantum and classical processes, it is usually assumed that if two parties interact only once with a physical medium, then only one-way influences are possible. Remarkably, this turns out to be an unnecessary restriction on the possible observable correlations. Formalised in the process matrix framework [1], where quantum theory is taken to hold locally but no global causal structure is assumed, some processes allow parties to establish correlations incompatible with a definite causal order. Causal nonseparability is the property underlying processes incompatible with a definite causal order. It can be certified in a device-independent way, i.e. requiring knowledge of the observed statistics only, based on the violation of causal inequalities by noncausal correlations. However, not all causally nonseparable process matrices are noncausal in this strong sense. Indeed, a large class of quantum-realisable processes cannot violate causal inequalities [2], and it is still unclear whether any physical process is able to. This includes the "quantum switch" [3], the canonical example of quantum circuits with quantum control of causal order, in which the causal order between two parties - Alice and Bob - is coherently controlled by a quantum system given to a third party, Fiona.

In this work [4], we present a method solely based on the observed correlations that certifies the causal nonseparability of all the processes that can induce a causally nonseparable distributed measurement [5], which includes all bipartite causally nonseparable processes and the celebrated quantum switch. This certification, that we labelled "network-device-independent" (NDI), is achieved by introducing a network of untrusted space-like separated operations allowing to self-test the quantum inputs received by the distributed measurement.

Another protocol, the "DRF" certification of the quantum switch [6], is based on the violation of a correlations inequality by Alice, Bob, Fiona, and a space-like separated party, Charlie. It consists in certifying that Charlie remotely controls the causal order of Alice and Bob's operations by maximally winning a heralded GYNI game, and certifying that the control is non-classical by violating a CHSH inequality between Fiona and Charlie.

Unlike our NDI certification which certifies causal nonseparability, a theory-dependent notion of indefinite causal orders, the DRF method certifies a theory independent notion of non-classical control of causal order. As noncontextuality [7] is generally considered as a standard notion of classical explainability for operational phenomena, this raises the question whether the causal nonseparability of the quantum switch might be explained by contextuality.

[1] O. Oreshkov, F. Costq and C. Brukner, "Quantum correlations with no causal order", Nature Communications 3, 1092 (2012).
[2] J. Wechs, H. Dourdent, A. Abbott and C. Branciard, "Quantum circuits with classical versus quantum control of causal order", PRX Quantum 2, 030335 (2021).
[3] G. Chiribella, G. M. D'Ariano, P. Perinotti, and B. Valiron, "Quantum computations without definite causal structure", PRA 88, 022318 (2013).
[4] H. Dourdent, A. Abbott, I. Šupić and C. Branciard, "Network-Device-Independent Certification of Causal Nonseparability", arXiv :2308.12760 [quant-ph] (2023).
[5] H. Dourdent, A. Abbott, N. Brunner, I. Šupić and C. Branciard, "Semi-Device-Independent Certification of Causal Nonseparability with Trusted Quantum Inputs", PRL 129, 090402 (2022).
[6] T. van der Lugt, J. Barrett and Giulio Chiribella, "Device-independent certification of indefinite causal order in the quantum switch", arXiv :2208.00719 [quant-ph] (2022).
[7] R. W. Spekkens, "Contextuality for preparations, transformations, and unsharp measurements", PRA 71, 052108 (2005).

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Toward spin-mechanical coupling in levitating 2D material

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We aim to investigate spin-mechanical coupling in levitating hBN particles with boron vacancy spin defects held in Paul traps. The substantial spin density and the potentially large angular confinement in these micro-particles may offer a new way to probe the physics of spin-defects in 2D materials

[1] T. Delord et al., "Spin-cooling of the motion of a trapped diamond", Nature **21** (2020).
[2] A. Gottscholl et al. "Initialization and read-out of intrinsic spin defects in a van der Waals crystal at room temperature", Nat. Mat. **19** (2020).
[3] A. Durand et al. "Optically active spin defects in few-layer thick hexagonal boron nitride", Phys. Rev. Lett. **131** (2023).

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Toward collective effects in ordered ensembles of dysprosium atoms

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Many cold-atom experiments currently rely on the trapping of single atoms in arrays of optical tweezers. These techniques have been developed over the past few years with alkali atoms then with alkaline-earth atoms. We have recently demonstrated the first trapping and imaging of single dysprosium atoms [1] in optical tweezers, extending the single atom toolbox to lanthanides. We will study collective dissipation in such an array which is interesting for future quantum technology applications. In fact when the emitters are at a distance of the order of λ, or a few multiples of λ, collective effects start to emerge as the dipoles can couple to one another at these distances. We make use of the very different linewidths of dysprosium to image site resolved excitations in an array of atoms and we plan to implement this technique to study collective dissipation by the ensemble.
We use the combination of a 32MHz broad transition at 421nm to efficiently cool the atoms at the output of the oven and a narrow 135kHz transition at 626nm to load a 3D MOT from which we can load an array of tweezers. Using the strong anisotropic light shift of dysprosium, we are able to trap the atoms in a magic condition which is necessary in our case to effectively image single atoms.
In order to observe these collective effects, we still need to be able to bring the atoms from a few micrometers (the current atom spacing in the tweezer array) to close to 600nm - the optical wavelength. We therefore plan to implement an accordion lattice on our experiment in the near future.

[1] D. Bloch, B. Hofer, A. Browaeys, I. Ferrier-Barbut, "Trapping and imaging single dysprosium atoms in optical tweezer arrays" (2023).

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GdR TeQ Quantum Abstract :
Magnon-magnon quantum entanglement and the phonon effects in antiferromagnetic structure

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Quantum magnonics is an emerging research field, with great potential for applications in magnon based hybrid systems and quantum information processing. Quantum correlation, such as entanglement, is a central resource in many quantum information protocols that naturally comes about in any study toward quantum technologies. This applies also to quantum magnonics. First, we investigate antiferromagnets in which sublattices with ferromagnetic interactions can have two different magnon modes, and we show how this may lead to experimentally detectable bipartite continuous variable magnon-magnon entanglement. The entanglement can be fully characterized via a single squeezing parameter, or, equivalently, entanglement parameter. The clear relation between the entanglement parameter and the Einstein, Podolsky, and Rosen (EPR) function of the ground state opens for experimental observation of magnon-magnon continuous variable entanglement and EPR nonlocality. Our recent work proposes a practical experimental realization to detect the EPR function of the ground state, in a setting that relies on magnon-photon interaction in a microwave cavity [1].

Our current study and outstanding result not only provide original evidence for creation and observation of tunable and robust entangled quantum states of magnons in a wide range of temperature including room temperature, but also expands the magnon applications from spintronics and quantum information processing to biomedical applications. The ability to produce quantum states with tunable and robust entanglement in ambient conditions has significant implications as it would avoid costly cooling procedures, reduce the effect of thermal noise, simplify the experimental setups, and widen the range of quantum applications [2].

[1] Vahid Azimi Mousolou, Yuefei Liu, Anders Bergman, Anna Delin, Olle Eriksson, Manuel Pereiro, Danny Thonig, and Erik Sjöqvist, Phys. Rev. B **104**, 224302 (2021) .
[2] Yuefei Liu, Andrey Bagrov, Anders Bergman, Anna Delin, Olle Eriksson, Manuel Pereiro, Simon Streib, Danny Thonig, Erik Sjöqvist, Vahid Azimi-Mousolou, arXiv :2209.01032 (2022).

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Optimising the interference between a classical and a quantum field for the measurement of Wigner functions

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Semiconductor quantum dots (QDs) have shown to be excellent systems to generate quantum light for discrete variable quantum information processing, producing single and entangled photons [1, 2]. These quantum emitters could also be of great use for continuous variable (CV) information processing [3], owing to their ability to add or substract a photon and generate photon-number superpositions [4, 5]. Homodyne detection, harnessing the interference of quantum and classical fields, is a key tool in the CV paradigm. The quality of homodyne detection is dependent on the mean wave-packet overlap M in all degrees of freedom (polarisation, spatial, frequency and timing) between the quantum and classical fields [6]. A high mode overlap is therefore crucial, for example, to observe non-Gaussianity and negativity in the Wigner function (WF) tomography of non-classical fields of light.

Here we report and experimentally implement a method to assess and optimise the parameter M [7] based on measuring the second-order correlation function, $g^{(2)}(\tau)$, between a classical field (a coherent state with mean photon number $|\alpha|^2$, dubbed a Local Oscillator, LO) and a single photon (SP) generated from our QD source. As shown in Fig.1(a), a LO and a SP are sent in the inputs of a fibre beam splitter (FBS) with transmissivity T and reflectivity R. One FBS-output, combining a coherent state with a mean number of photons $R|\alpha|^2$ and a stream of single photons, is sent into a Hanbury-Brown-Twiss (HBT) setup including two single photon detectors, D_1 and D_2. The second order correlation function $g^{(2)}(\tau)$ between D_1 and D_2 exhibits a bunching behaviour, shown in Fig. (1c) (red points), for $R|\alpha|^2$ close or larger than the transmitted mean photon number of the single photons $T\eta = (7 \pm 0.2) \times 10^{-2}$, where η is the efficiency of the single photon source. This bunching is confirmed by observing the histogram with $R|\alpha|^2 = 7.5 \times 10^{-2}$, exhibiting a higher central peak, as shown in Fig. 1(b). We introduce a mode mismatch by changing the polarisation of $|\alpha\rangle$. According to simulations following [7], M is decreased from ~ 0.58 (red) to ~ 0.02 (black). Owing to the high efficiency of the QD source, such measurement can be conducted in real time to optimize the mean wavepacket overlap, constituting a first step to tap the potential of QD devices for CV quantum information processing.

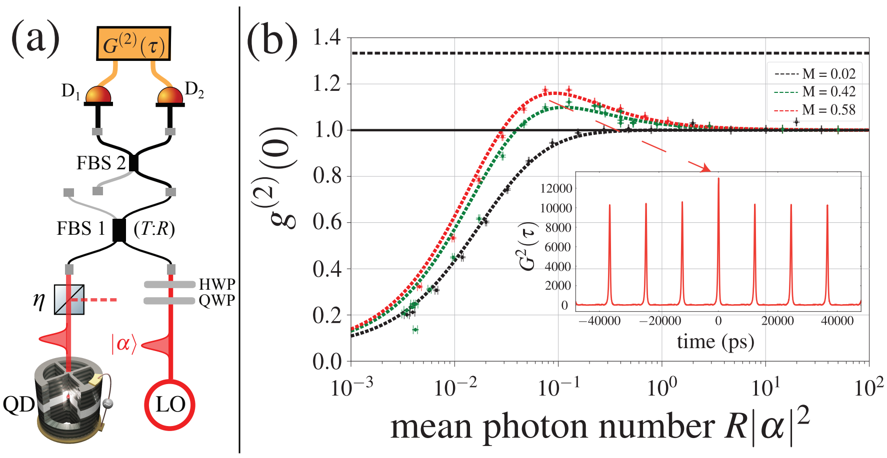

FIGURE 1 – (a) Experimental setup for the interference between a LO $|\alpha\rangle$ and SP, occurring in a FBS with reflectivity R and transmissivity T. One output of this FBS is analysed in a HBT setup. The efficiency of the $|1\rangle$-channel is represented by η. (b) Depicts the values of the normalised 2nd-order intensity correlation function $g^{(2)}(0)$ on (D_1, D_2) measured for different values of $|\alpha|^2$, with theoretical curves shown as dashed lines. The inset of this figure shows a second order correlation function histogram for $R|\alpha|^2 = 7.5 \times 10^{-2}$ for $M \approx 0.58$.

[1] N. Somaschi, V. Giesz, L. D. Santis, J. C. Loredo, M. P. Almeida, G. Hornecker, S. L. Portalupi, T. Grange, C. Antón, J. Demory, et al., Nature Photonics **10**, 340 (2016).
[2] N. Coste, D. A. Fioretto, N. Belabas, S. C. Wein, P. Hilaire, R. Frantzeskakis, M. Gundin, B. Goes, N. Somaschi, M. Morassi, et al., Nature Photonics **17**, 582 (2023).
[3] M. Walschaers, PRX Quantum **2** (2021).
[4] L. D. Santis, C. Antón, B. Reznychenko, N. Somaschi, G. Coppola, J. Senellart, C. Gómez, A. Lemaître, I. Sagnes, A. G. White, et al., Nature Nanotechnology **12**, 663 (2017).
[5] J. C. Loredo, C. Antón, B. Reznychenko, P. Hilaire, A. Harouri, C. Millet, H. Ollivier, N. Somaschi, L. De Santis, A. Lemaître, et al., Nature Photonics **13**, 803 (2019), ISSN 1749-4893.
[6] K. Laiho, K. N. Cassemiro, D. Gross, and C. Silberhorn, Phys. Rev. Lett. **105**, 253603 (2010).
[7] P. Steindl, Ph.D. thesis, Leiden University (2023).

Maximum possible violations of 2-outcome Bell Inequalities with homodyne measurements

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Bell inequalities are at the heart of Quantum Information. Initially, their goal was to establish if quantum theory had to be complemented by hidden variables and if Nature could be modelled by local deterministic models. However, following the "second quantum revolution", the violation of a Bell inequality was shown to be a resource for quantum communication [1–3].

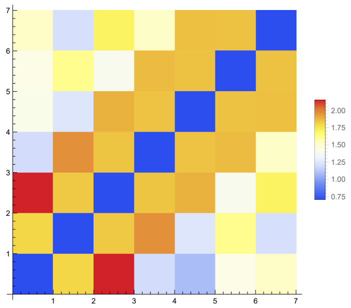
By 2017, three different Bell experiments had been carried out which closed the main "loopholes", *i.e.* experimental problems that affect the validity of Bell tests [4–6]. However, these experiments used entanglement implemented in matter, such as NV centers, which implied heavy set-ups that needed very low temperature and runs over long period. In contrast, we focused on quantum optics set-ups with the most elementary measurement apparatus, that is homodyne detectors, and we obtained the best possible Bell inequality violations in that case.

For every inequality, we run optimisations to obtain the maximum quantum bound, by playing on three different parameters :

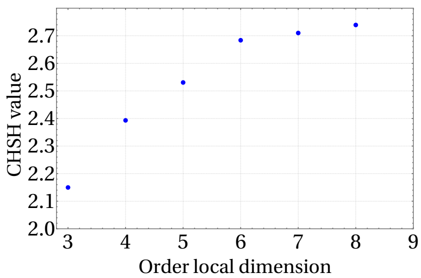
— The dimension of the observables
— The angles of the homodyne measurements
— The choice of binning.

Homodyne detectors yield outcomes in $\mathbb{R}$; a binning consists in discretizing this outcome into ± 1 in order to fit to Bell inequalities format. We show that if we consider qubit spaces, the only one which can produce non-locality is $\{|0\rangle, |2\rangle\}$ as displayed in Fig. (a). The violation of non locality an experimentalist can obtain rapidly increases as we allow for qudit spaces of increasing dimension $n+1$, $\{|0\rangle, |1\rangle, ..., |n\rangle\}$ as displayed in Fig. (b).

In order to propose realistic set-ups for experiments, we run the same kind of optimisation, after having taken into account the noise inherent to the apparatus. We compute the minimum efficiency required to obtain Bell violation with homodyne measurements given a dimension up to 8. Finally, instead of looking for a state associated to a violation, we directly optimize on set-ups : our cost function is a Bell score as a function of the different possible optics one can put in a circuit.



(a) Best possible CHSH score for a qubit system $\{|n\rangle, |m\rangle\}$, based on the optimisation of the trace-norm of this qubit.



(b) Maximum possible quantum values for the CHSH inequality as a function of the local dimension of the observables.

[1] A. Ekert, "Quantum cryptography based on Bell's theorem", Phys. Rev. Lett.. **67-6**, 661–663 (1991).
[2] S. Pironio, A. Acín, S. Massar *et.al*, "Random numbers certified by Bell's theorem", Nature. **464-7291**, 1021–1024 (2010).
[3] , A. Acín, N. Gisin, L. Masanes, "From Bell's Theorem to Secure Quantum Key Distribution", Phys. Rev. Lett.. **97-12**, 120405 (2006).
[4] , M. Giustina, M. Versteegh, S. Wengerowsky *et al.*, "Significant-loophole-free test of Bell's theorem with entangled photons", Phys. Rev. Lett.. **115-25**, 250401 (2015).
[5] , B. Hensen, H. Bernien, A.E. Dréau *et al.*, "Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres", Nature. **526-7575**, 682–686 (2015).
[6] , L. K. Shalm, E. Meyer-Scott, B.G. Christensen *et al.*, "Strong loophole-free test of local realism", Phys. Rev. Lett.. **115-25**, 250402 (2015).

Formalizing the notion of dynamical causal order for quantum circuits with quantum control

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Abstract

The process matrix formalism was introduced to describe processes through which different agents establish correlations by locally performing quantum operations, although without requiring the assumption that they must follow a well-defined global causal order [1]. Indeed the formalism allows for processes that exhibit so-called *indefinite causal order*. The *quantum switch* [2] is a canonical example of such processes, where the two possible causal orders between two agents A and B, namely "A before B" and "B before A", are superposed in a coherent manner, leading to a so-called *causal superposition.*

In the quantum switch construction, and in its natural generalizations to more agents, the agents never intervene on the causal order itself. Yet, as soon as more than two agents are considered, an agent A could influence the causal order between two agents B and C that are in the future of A. This illustrates the notion of dynamical causal order [3], which can be encountered in general relativity; and, combined with causal superpositions, which may be expected to arise in a theory of quantum gravity.

In this work we explore this idea of combining causal superpositions with dynamical causal orders. We consider the recently introduced class of quantum circuits with quantum control (QC-QC) of the causal order [4], which is the largest class within the process matrix formalism known to have a clear interpretation in terms of coherent superpositions of causal orders. This class includes examples of quantum processes (such as the so-called *Grenoble process* [4]) that are not just generalisations of the quantum switch: these exhibit qualitatively different features, which intuitively correspond to dynamical orders. We formalise precisely this notion for causal superpositions. This leads us to characterize the new class of *non-dynamical processes*. We show that the quantum switch, and all its generalizations, belong to this class, while the Grenoble process and other QC-QCs indeed go beyond. In order to strengthen our formalization of dynamical yet indefinite causal orders, we shall look at the correlations created by such non-dynamical processes, and understand whether they correspond to the notion of non-dynamical correlations proposed in [5].

References

[1] Ognyan Oreshkov, Fabio Costa, and Časlav Brukner. Quantum correlations with no causal order. *Nat. Commun.*, 3:1092, 2012.

[2] Giulio Chiribella, Giacomo Mauro D'Ariano, Paolo Perinotti, and Benoit Valiron. Quantum computations without definite causal structure. *Phys. Rev. A*, 88:022318, 2013.

[3] Lucien Hardy. Probability theories with dynamic causal structure: a new framework for quantum gravity. *arXiv preprint gr-qc/0509120*, 2005.

[4] Julian Wechs, Hippolyte Dourdent, Alastair A. Abbott, and Cyril Branciard. Quantum circuits with classical versus quantum control of causal order. *PRX Quantum*, 2:030335, Aug 2021.

[5] Alastair A Abbott, Christina Giarmatzi, Fabio Costa, and Cyril Branciard. Multipartite causal correlations: polytopes and inequalities. *Physical Review A*, 94(3):032131, 2016.

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A spin coupled to light

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Spins in semiconductor quantum dots constitute a promising platform for scalable quantum information processing [1]. Coupling them strongly to the photonic modes of superconducting microwave resonators would enable fast non-demolition readout and long-range, on-chip connectivity, well beyond nearest-neighbor quantum interactions [2]. Previous work in our team demonstrated spin-photon coupling rate as high as 330 MHz largely exceeding the decoherence rate of the spin, opening a path towards hybrid spin circuit quantum electrodynamics [3]. We present here following results on the dissipation and decoherence of our spin state coupled to light showing that the relaxation mechanism is mostly dominated by photon emission, similarly to what has been found in the past for transmons [4], while the decoherence mechanism is yet to be explained.

[1] G. Burkard, et sl., "Semiconductor spin qubits", Rev. Mod. Phys **95**, 25003 (2023).

[2] A. Blais, et al., "Cavity quantum electrodynamics for superconducting electrical circuits : An architecture for quantum computation", PRA **69**, 062320 (2004).

[3] C. X. Yu, et al., "Strong coupling between a photon and a hole spin in silicon", Nat. Nanotechnol. **18**, 741-746 (2023).

[4] A. A. Houck, et al., "Controlling the Spontaneous Emission of a Superconducting Transmon Qubit", Phys. Rev. Lett. **101**, 080502 (2008).

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Data acquisition for state engineering in multimode context

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Non Gaussian quantum states of light belong to the basic set of tools needed in numerous quantum information protocols including measurement based quantum computation and quantum communication [1]. Consequently, the protocols for generating these states have been extensively studied by the scientific community. Research teams worked on heralded protocols and show significants results [2, 3]. However, these protocols are sensible to losses, detection efficiency and detection bandwidth. Remarkably, in multiple situations optical filtering steps are required on the heralding path to comply with spectral multimode features [4–6].This leads to a time envelop that needs to be resolved to observe the produced non gaussian state [7]. In that context, the performances of detectors on the heralded path become a critical factor. In recent works, high performance (bandwidth and detection) detectors are used to avoid this issue. Here, we analyze experimental data to characterize the boundary between optimal working parameters and unoptimal experimental resources. Our approach provides a framework for detecting and reconstructing a non gaussian state with a given fidelity and at a given heralding rate, allowing to perform state generation protocol using standard detectors and still having high quality results in terms of measured heralded states.

We focus on the data acquisition strategy used in our work on the plug'n'play generation of non-Gaussian states of light at a telecom wavelength [6]. Since we consider a continuous wave laser for the local oscillator, data are post treated to make the detection mode on the homodyne used to measure the produced the non Gaussian state match the heralding detection mode determined by the optical filters. The post-treatment stage is a multimode analysis using eigenfonctions expansion of the autocorrelation fonction [8]. This process allows us to access the temporal mode from the experimental data.

In this work we implement this treatment but varying key parameters : the bandwidth of the homodyne photodetection B_{HD} and the sampling rate of the oscilloscope f_s. The figure **1** shows an extracted profile and a schematic visualisation of the role of these parameters. Our investigation delves into two primary ideas : identifying a threshold for the sampling rate to reconstruct the temporal profile and evaluating the reconstruction quality for decreasing bandwidth.

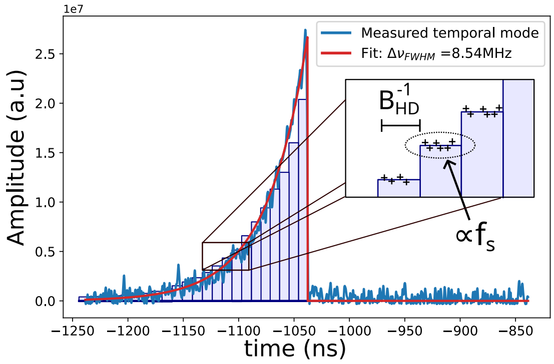

Figure 1 Extracted temporal profile.

Our work provides a framework to identify accurate detection and reconstruction of non-Gaussian quantum states. These findings signify a significant step towards practical uses of non-Gaussian quantum states into modern quantum technologies.

[1] A. I. L. et al., "Production and applications of non-gaussian quantum states of light," (2020), arXiv :2006.16985.
[2] Y.-S. Ra, A. Dufour, M. Walschaers, C. Jacquard, T. Michel, C. Fabre, and N. Treps, Nature Physics **16**, 144 (2020).
[3] M. E. et al, Opt. Express **31**, 12865 (2023).
[4] M. F. Melalkia, L. Brunel, S. Tanzilli, J. Etesse, and V. D'Auria, Physical Review A **105**, 013720 (2022).
[5] O. al., Physical Review Letters **116**, 233602 (2016).
[6] M. F. Melalkia, T. Gabbrielli, A. Petitjean, L. Brunel, A. Zavatta, S. Tanzilli, J. Etesse, and V. D'Auria, Opt. Express **30**, 45195 (2022).
[7] Z. Qin, A. S. Prasad, T. Brannan, A. MacRae, A. Lezama, and A. Lvovsky, Light : Science & Applications **4** (2015).
[8] O. Morin, C. Fabre, and J. Laurat, Phys. Rev. Lett. **111**, 213602 (2013).

Engineering and understanding plasma modes in the fluxonium qubit

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In the fluxonium circuit [1], a small Josephson Junction (JJ) is shunted by a very large inductance known as superinductance. Superinductors typically consist of an array of JJ's (Typically, an array has hundreds to thousands of JJ in series). Achieving superinductors in the range of fractions of μH can be accomplished by using the kinetic inductance of arrays of JJ [2, 3], or a nanowire made of disordered superconductors [4]. Achieving an even larger inductance value is highly desirable, especially for protected qubits applications [5].

For Josephson array inductors, the higher inductance is typically achieved by increasing the array's length. Adding increased length to the array inevitably comes with additional capacitance to the ground (C_g). The combination of distributed inductance and capacitance creates collective excitations known as plasma modes. The presence of these spurious degrees of freedom within the circuit can have a detrimental impact on its coherence [6].

In this work, our objective is to understand these plasma modes comprehensively. We aim to predict their frequency and their interactions with the fluxonium circuits. We will introduce a novel fabrication technique based on wet and dry etching methods to remove silicon near the superinductor, minimize C_g, and push the plasma mode to higher frequencies. Preliminary analysis with finite element electromagnetic simulations indicates a substantial decrease in C_g, when the substrate is etched to a depth approximately five times the separation between two JJ chains.

[1] Manucharyan, V. E., Koch, J., Glazman, L. I. and Devoret, M. H. Fluxonium : Single Cooper-pair circuit free of charge offsets. Science 326, 113–116 (2009).

[2] N. A. Masluk, I. M. Pop, A. Kamal, Z. K. Minev, and M. H. Devoret, "Microwave characterization of josephson junction arrays : Implementing a low loss superinductance," Physical Review Letters, vol. 109, p. 137002, 2012

[3] I. V. Pechenezhskiy, R. A. Mencia, L. B. Nguyen, Y.-H. Lin, and V. E. Manucharyan, The superconducting quasicharge qubit, Nature 585, 368 (2020).

[4] T. Hazard, A. Gyenis, A. Di Paolo, A. Asfaw, S. A. Lyon, A. Blais, and A. A. Houck, Nanowire Superinductance Fluxonium Qubit, Phys. Rev. Lett. 122, 010504 (2019).

[5] Groszkowski, P., Paolo, A. D., Grimsmo, A. L., Blais, A., Schuster, D. I., Houck, A. A., and Koch, J. (2018). Coherence properties of the 0-pi qubit. New Journal of Physics, 20(4), 043053.

[6] Manucharyan, V. E., Masluk, N. A., Kamal, A., Koch, J., Glazman, L. I., and Devoret, M. H. (2012). Evidence for coherent quantum phase slips across a Josephson junction array. Physical Review B, 85(2), 024521.

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Decoherence as a high-dimensional geometrical phenomenon

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The material for this talk is based on a paper [1] which has almost passed peer review and will soon be published in *Foundations of Physics*.

The theory of decoherence is arguably one of the greatest advances in fundamental physics of the past forty years. Without adding anything new to the quantum mechanical framework, and considering that the Schrödinger equation is universally valid, it explains why quantum interferences virtually disappear at macroscopic scales. Since the pioneering papers [2][3], a wide variety of models have been designed to understand decoherence in different specific contexts. In this talk, however, we would like to embrace a more general point of view and understand the mathematical reason why decoherence is so ubiquitous between quantum mechanical systems.

We start by introducing general quantities and notations to recall as concisely as possible the idea underlying the theory of decoherence. We then build a simple but very general model for a purely random environment, which reveals the mathematical mechanisms that make decoherence so universal. First, the well-known typical decay (already obtained by Zurek in [4]) of the non-diagonal terms of the density matrix in $n^{-\frac{1}{2}}$ is recovered, with n the dimension of the Hilbert space describing the environment. The most important result is a theorem, giving quantitative estimates for the level of decoherence induced by a random environment on a system of given sizes. We conclude that even very small environments (of typical size at least $N_{\mathcal{E}} = \ln(N_{\mathcal{S}})$ with $N_{\mathcal{S}}$ the size of the system) suffice, which is not good news for quantum computing... The (strong) assumptions of the model are discussed in the end of the talk, but possible improvements lead to interesting directions of research, in particular trying to describe the submanifold of truly reachable states in the Hilbert space, a question that could possibly be answered using the tensor networks theory and the area law for entanglement entropy. Finally, we also give a general formula estimating the level of classicality of a quantum system in terms of the entropy of entanglement with its environment.

[1] A. Soulas, "Decoherence as a high-dimensional geometrical phenomenon", arXiv preprint arXiv :2302.04148 (2023).
[2] H. D. Zeh, "On the interpretation of measurement in quantum theory", Foundations of Physics (1970).
[3] W. H. Zurek, "Pointer basis of quantum apparatus : Into what mixture does the wave packet collapse ?", Physical review D (1981).
[4] W. H. Zurek, "Environment-induced superselection rules", Physical review D (1982).

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Fast-flux tuning of the dispersive shift between a Fluxonium and it's readout resonator

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Realizing fault-tolerant quantum computing requires qubits with longer coherence time as well as fast and efficient ways to readout and manipulate them. Recently, in the family of superconducting qubits, Fluxonium qubits have gained a lot of attention thanks to its record coherence time [1] and fast gate operation [2, 3]. The Fluxonium is a highly anharmonic multi-level system made of a high-impedance superconducting loop interrupted by a small Josephson junction.

As opposed to a true spin-1/2 off-resonantly coupled to a harmonic oscillator (Jaynes-Cummings model), the calculation of the dispersive shift between a Fluxonium and a microwave cavity involves the detuning and the couplings to all the higher transitions of the circuit [4], whose values vary strongly with the external magnetic flux threading the circuit's loop.

In this work, we will describe the implementation of a fast-flux line (FFL) in a Fluxonium architecture. We show that using a FFL, it is possible to dynamically change the dispersive shift, χ between the qubit and the readout resonator. This new method allows to change the dispersive shift from zero during gate operations to protect the qubit from photon shot noise to values exceeding several megahertz for efficient readout.

[1]] A. Somoroff, Q. Ficheux, R. A. Mencia, H. Xiong, R. Kuzmin, and V. E. Manucharyan, "Millisecond Coherence in a Superconducting Qubit", Phys. Rev. Lett. **130**, 267001 (2023).
[2] Q. Ficheux, L. B. Nguyen, A. Somoroff, H. Xiong, K. N. Nesterov, M.G. Vavilov, and V. E. Manucharyan, "Fast Logic with Slow Qubits : Microwave-Activated Controlled-Z Gate on Low-Frequency Fluxoniums", Phys. Rev. X **11**, 021026 (2021).
[3] L. Ding et al., "High-Fidelity, Frequency-Flexible Two-Qubit Fluxonium Gates with a Transmon Coupler", arXiv :2304.06087 (2023).
[4] G. Zhu, D. G. Ferguson, V. E. Manucharyan, and J. Koch, "Circuit QED with fluxonium qubits : Theory of the dispersive regime", Phys. Rev. B **87**, 024510 (2013).

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Emergence of decoherence in rare-earth ion-doped crystals from coupling between ion species

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Rare-earth ion doped crystals (in particular rare-earth ion-doped yttrium orthosilicate Y_2SiO_5), have emerged as promising platforms for the storage and on-demand reading of quantum information, thanks to their large multiplexing capabilities and excellent optical and spin coherence properties at cryogenic temperatures. Experimental observations showed that the application of a magnetic DC bias field influences significantly the coherence time in the rare-earth ions ensemble [1, 2], but no precise estimate have been given in term of coherence time as a function of amplitude and direction of the magnetic field, especially for magnetic field amplitudes under the mT.

We investigate the relationship between the magnetic field parameters and the decoherence caused by the dipole-dipole couplings between the ions species in the crystalline matrix that possess a nuclear spin (in our case, the yttrium and rare-earth ions). We chose a microscopic approach for our simulations, by simulating a system composed of one rare-earth ion surrounded by a few yttrium ions. The results guided us on identifying different behaviors of the system that corresponds to different magnetic field regimes, and led us to give coherence time values for different magnetic fields configurations and rare-earth species (ytterbium, europium and praseodymium). With these results, we aim to give guidance in order to chose optimal magnetic fields settings to reach long coherence times without the constraint to be in more specific regimes.

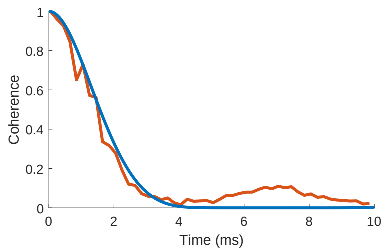

FIGURE 1 – Coherence decay in Ytterbium at 66 μT, experimental data (in orange) [1] and simulation (in blue) for one Ytterbium ion and five Yttrium ions.

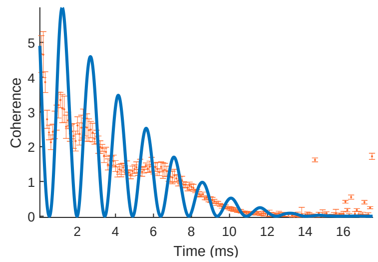

FIGURE 2 – Coherence decay in Europium at 60 μT, experimental data (in orange) [3] and simulation (in blue) for one Europium ion and five Yttrium ions.

[1] Nicolas, L., Businger, M., Sanchez Mejia, T. et al. Coherent optical-microwave interface for manipulation of low-field electronic clock transitions in $^{171}Yb^{3+}$: Y_2SiO_5. npj Quantum Inf 9, 21 (2023).

[2] B. Car, J.-L. Le Gouët, and T. Chanelière. Superhyperfine induced photon-echo collapse of erbium in Y_2SiO_5. Phys. Rev. B 102, 115119 (2020).

[3] Antonio Ortu, Adrian Holzäpfel, Jean Etesse and Mikael Afzelius, Storage of photonic time-bin qubits for up to 20 ms in a rare-earth doped crystal, npj Quantum Information volume 8, Article number : 29 (2022).

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