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Quantum PhD & Job Fair / Forum des thèses et métiers du quantique
November 13, 2024
Sorbonne University, 4 place Jussieu, 75005 Paris

INTERNSHIP PROPOSAL

Laboratory name: Institut de Physique Théorique (IPhT)
CNRS identification code: DRF-INP UMR 3681
Internship director's name: Jean-Daniel BANCAL
e-mail: jdbancal.physics@gmail.com
Web page: https://quantum.paris
Internship location: Orme des Merisiers bât. 774, CEA Paris-Saclay, 91191 Gif-sur-Yvette
Thesis possibility after internship: yes
Funding: no

Limits of Quantum Correlations

As a theory for physical phenomenons, quantum theory has the curious feature that it does not actually predict the results that are to be observed in an experiment, but only their statistical distribution. This fundamentally probabilistic nature has deep consequences both on our understanding of the theory and on the potential applications that can be built with it. Indeed, quantum correlations are at the root of Bell experiments, which are some of the most fundamental tests of nature to date as recognized by the 2022 Nobel prize. At the same time, quantum correlations allow for new kinds of practical tasks with unparalleled security guarantees, known as device-independent protocols [1]. More generally, quantum statistics play a key role throughout quantum information theory, all the way from quantum computing to many-body physics.

Yet, quantum correlations remain poorly understood. While some methods have been proposed to approach these statistics, they are generally either partial or implicit.

The aim of this internship is to identify some explicit regions of the quantum boundary analytically. This work will build on two recent results which identified a series of extremal quantum statistics [2], and constructed the first extreme tests for quantum statistics [3]. It will involve analytic and possibly numerical tools from non-commutative optimization, convex duality, and the quantum formalism.

By providing new ways of testing whether some statistics admit a quantum explanation or not, this work will help to characterize both the power and the limitations of quantum predictions. It may also lead to applications in self-testing and the certification of quantum technology devices, as well as in the study of quantum networks.

[1] Nadlinger et al., *Experimental quantum key distribution certified by Bell's theorem*, arXiv:2109.14600
[2] Barizien et al., *Quantum statistics in the minimal scenario*, arXiv:2406.09350
[3] Barizien et al., *Extremal Tsirelson inequalities*, arXiv:2401.12791

Master Internship Offer in Computer Science

Formal Verification of Contextuality-related Quantum Properties

Director: A. Giorgetti
Institution: Université de Franche-Comté
Laboratory: Institut FEMTO-ST (UMR CNRS 6174)
Department: Département d'Informatique des Systèmes Complexes (DISC)
Team: VESONTIO (Verification and validation of software and embedded systems)
Location: 16 route de Gray, 25030 Besançon cedex, France
Duration: 4-6 months
Expected start date: between March 2025 and June 2026
Deadline for application: four months before the beginning of the internship
Contact: alain.giorgetti@femto-st.fr

1 Scientific context

Contextuality is a quantum phenomenon that contributes significantly to the superiority of quantum programs, compared to their classical counterparts. However, there is still much to discover, understand and explain about how this benefit works.

Formal verification brings together various techniques of verification based on formal models. We consider more particularly two of these techniques, namely property-based testing and deductive verification, and their tooling related to the Why3 framework. Deductive verification consists in using a computer to assist the production of rigorous proofs of mathematical properties. It is applied in software engineering to increase confidence in software, by checking program properties. These techniques and the corresponding tools are gradually adapted to quantum programs, but much remains to be done.

Regarding contextuality, some properties are known, but they have often been obtained either by manual mathematical calculations or by automated calculations for a small number of quantum bits. We propose to assist the verification of these properties, and the discovery of other analogous properties, in particular with the aid of proof assistants, such as Why3 [BFM+18] or Coq [Coq89], to establish these properties with certainty and regardless of the number of quantum bits.

This challenge will be met through adaptations of formal proof and automatic test techniques, based on the current research results in verification of quantum programs. Particular attention will be paid to characterizations of contextuality based on contextual geometries [SDHG21, DHGM21, DHG+22, MSG+22, MSG+24a, MSG+24b, SHK+24, MG24].

2 Work environment and framework

The research will take place at the premises of the DISC department at the FEMTO-ST institute, located in Besançon, France. The PhD student will settle in the VESONTIO research team, whose research domains are the formal specification and verification of programs by test or by proof, based on program models. The is funded by the PEPR integrated project EPiQ ANR-22-PETQ-0007, part of Plan France 2030 (`https://project.inria.fr/epiq/`).

Within the collaborative project EPiQ, we study quantum contextuality with a geometrical and a combinatorial perspective. The investigation of the tensor structure of the Hilbert space of quantum (pure) multipartite systems and/or multi-operators (generalized Pauli groups) by means of algebraic-geometric techniques have started in different places in the world[1]. This approach has shed some new light on the concepts of entanglement and contextuality.

3 Internship subject and objectives

In a few words, the subject of the internship is to take up the challenge of the formal specification and verification of properties related to the phenomenon of quantum contextuality. The student is expected to achieve the following objectives:

- Learning how to use and using a verification platform like Why3 [BFM+18] or Coq [Coq89] to specify and formally demonstrate properties linked to the phenomenon quantum of contextuality.
- Learning how to use and using a testing tool like AutoCheck [EG20, GRE22, EGR22] to test these quantum properties before formally demonstrating them.
- In the input languages of these tools, formalization of some known contextuality properties.
- Formal proofs of some of these properties with Why3 and/or Coq.
- Dissemination of this work in the international scientific community.

4 Candidates profile and application

The candidate should be enrolled in a master program and have skills in the general area of formal methods, formal specification, verification and validation. Skills in Why3 or Coq proof environments will be appreciated. Proficiency in English is important, and the candidates shall master writing and presenting scientific work.

The application consists of one PDF file comprising:

- a CV,
- a letter of motivation justifying the interest for this particular PhD subject,
- the transcript of available records of the license and master degree (or equivalent),
- if possible, a certificate of language level in French and English.

The application should be sent by e-mail to `alain.giorgetti@femto-st.fr`.

Applications will be reviewed upon receipt. Short-listed candidates may be contacted for an online interview. The recruitment process ends when a sufficient number of adequate applications has been processed. The duration and the expected start date can be adapted to the requirements of the applicant, its master program and the research team.

For inquiries or more information about this internship, do not hesitate to contact me directly by e-mail.

References

[BFM+18] F. Bobot, J.-C. Filliâtre, C. Marché, G. Melquiond, and A. Paskevich. *The Why3 Platform*, 2018. `http://why3.lri.fr/manual.pdf`.

[Coq89] The Coq Proof Assistant, 1989. `http://coq.inria.fr`.

[DHG+22] Henri De Boutray, Frédéric Holweck, Alain Giorgetti, Pierre-Alain Masson, and Metod Saniga. Contextuality degree of quadrics in multi-qubit symplectic polar spaces. page 36, 2022. `https://arxiv.org/abs/2105.13798v2`, under submission.

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[1] The Simons Institute for the theory of computing organized in 2014 a one semester program on algorithm complexity and algebraic geometry. Among the various workshops proposed, one was focusing on “tensors in computer science and geometry” with specific talks on entanglement from a geometric perspective: `https://simons.berkeley.edu/workshops/schedule/432`

[DHGM21] Henri De Boutray, Frédéric Holweck, Alain Giorgetti, and Pierre-Alain Masson. Automated detection of contextuality proofs with intermediate numbers of observables. In *18th International Conference on Quantum Physics and Logic (QPL 2021)*, page 3, Gdańsk, Poland, jun 2021.

[EG20] C. Erard and A. Giorgetti. Random and enumerative testing tool for OCaml and WhyML, 2020. `https://github.com/alaingiorgetti/autocheck`.

[EGR22] Clotilde Erard, Alain Giorgetti, and Jérome Ricciardi. Towards random and enumerative testing for OCaml and WhyML properties. *Software Quality Journal*, 30(1):253–279, March 2022.

[GRE22] Alain Giorgetti, Jérome Ricciardi, and Clotilde Erard. Test aléatoire et énumératif pour OCaml et Why3. In *AFADL 2022*, 2022.

[MG24] Axel Muller and Alain Giorgetti. An abstract structure determines the contextuality degree of observable-based Kochen-Specker proofs, 2024.

[MSG$^+$22] Axel Muller, Metod Saniga, Alain Giorgetti, Henri De Boutray, and Frédéric Holweck. Multi-qubit doilies: enumeration for all ranks and classification for ranks four and five. page 14, 2022. `https://arxiv.org/abs/2206.03599`, under submission.

[MSG$^+$24a] Axel Muller, Metod Saniga, Alain Giorgetti, Henri de Boutray, and Frédéric Holweck. New and improved bounds on the contextuality degree of multi-qubit configurations. *Mathematical Structures in Computer Science*, 34(4):322–343, 2024.

[MSG$^+$24b] Axel Muller, Metod Saniga, Alain Giorgetti, Frédéric Holweck, and Colm Kelleher. A new heuristic approach for contextuality degree estimates and its four- to six-qubit portrayals, 2024. Under submission.

[SDHG21] Metod Saniga, Henri De Boutray, Frédéric Holweck, and Alain Giorgetti. Taxonomy of polar subspaces of multi-qubit symplectic polar spaces of small rank. *Mathematics*, 9(18), sep 2021.

[SHK$^+$24] Metod Saniga, Frédéric Holweck, Colm Kelleher, Axel Muller, Alain Giorgetti, and Henri de Boutray. Hexagons govern three-qubit contextuality, 2024. Under revision, preliminary version `https://arxiv.org/abs/2312.07738`.

Offer: 6-month Master 2 Internship

Microcell physics package for miniaturized Rb optical clock

Context:

The convergence of atomic spectroscopy, MEMS technologies and integrated photonics has allowed the development of high-precision **chip-scale atomic devices** [1]. Among these instruments, **miniaturized atomic clocks** with unrivaled size-power-frequency instability budget (16 cm^3, 120 mW, 1 µs/day) have been demonstrated and are now widely deployed in navigation systems, instrumentation, metrology, and communications. However, these **microwave** chip-scale atomic clocks (CSACs), based on the interaction of hot alkali atoms (Cs or Rb) confined in a micro-fabricated cell with an optically-carried microwave signal, suffer from limitations and approach their ultimate performances.

In response, last years have seen the emergence of new-generation chip-scale **optical** atomic clocks [2-3]. In a miniaturized optical frequency reference, the frequency of a narrow-linewidth laser is stabilized onto a narrow optical atomic resonance detected in a microfabricated alkali vapor cell.

In this domain, we work at FEMTO-ST on the development of a **microcell optical clock** based on **two-photon transition of the Rb atom** at 778 nm. In this system, atoms in a MEMS cell are excited by two counter-propagation light fields provided by a single laser at 778 nm. Atoms are then promoted to an excited state from which they spontaneously decay. During their radiative cascade, atoms emit blue fluorescence photons at 420 nm that are detected by a photomultiplier. The latter delivers the narrow atomic response used to lock the frequency of the laser.

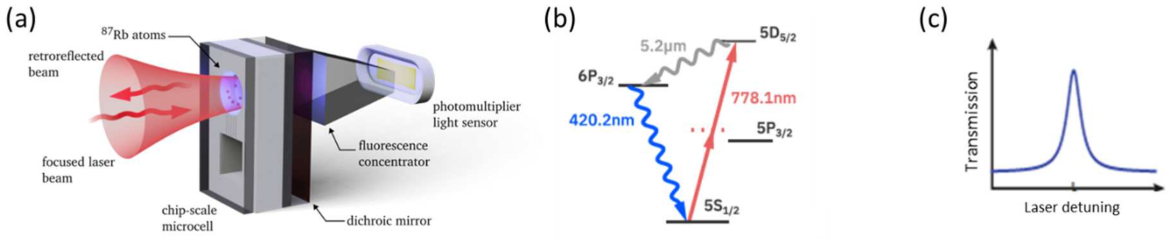


Figure 1: (a) Illustration of two-photon spectroscopy in Rb atom microcell (b) Involved energy levels in the atom-light interaction. (c) Resonance detected in a Rb MEMS cell.

Our table-top prototype at FEMTO-ST achieves a short-term fractional frequency stability of **3x10^{-13} at 1 s** [4], which is approximately **1000 times better than commercial microwave CSACs**. If already remarkable, such microcell clock architectures still have significant room for improvement. Achieving stability in the **10^{-14} range** with this type of clock seems to be feasible. This M2 internship is proposed within this context.

Training Subject:

The short-term fractional frequency stability of our Rb microcell clock is currently limited by a relatively weak atomic resonance signal. This limited signal is attributed to the finite active volume where atom-light interaction occurs and the fact that only a fraction of the emitted blue photons are collected by the photomultiplier. It is therefore necessary to develop original cell architectures and associated physics packages in order to increase the number of atoms participating to the two-photon transition and the number of collected blue photons.

During the 6-month training, the candidate will contribute to the design (mechanical and optical), simulation (thermal/magnetic), development and characterization of an original microcell physics package. Studies will rely on a novel microcell design under-progress at FEMTO-ST. The physics package will embed the microfabricated cell, several optical components to ensure the generation of the retro-reflected beam (for stimulation of the two-photon transition), and the photomultiplier to detect the blue photons. All this will be configured in an optimal way such that the atomic signal response will be as high as possible. All these elements should be embedded and mechanically fixed into a magnetically-shield and thermally-controlled ensemble. After design and simulation, the microcell physics package will be developed, mounted and implemented in a Rb 778 spectroscopy setup. Detection of the two-photon transition and characterization of the atomic resonance with some key parameters (laser intensity, cell temperature) will then be performed.

Bibliography
[1] J. Kitching, Appl. Phys. Rev. 5, 031302 (2018). https://doi.org/10.1063/1.5026238
[2] V. Maurice et al., Opt. Exp. 28, 17, 24708 (2020). https://doi.org/10.1364/OE.396296
[3] Z. L. Newman et al., Opt. Lett. 46, 18, 4702 (2021). https://doi.org/10.1364/OL.435603
[4] M. Callejo et al., ArXiV 2407 :00841 (2024). https://arxiv.org/pdf/2407.00841

M2 Candidate Profile

The candidate should appreciate applied physics disciplines in general, for working in a highly-interdisciplinary subject. The candidate should have a good knowledge, and ideally competences, with optics, mechanical design, electronics, coding (Python preferred) and be attracted by high-precision metrology. Some knowledge with atomic physics is a clear plus-value but is not mandatory. Some background, through lab works for example, with clean-room techniques and processes might be an additional plus-value.

Training environment

The M2 candidate will work at the interface between the OHMS group (http://teams.femto-st.fr/equipe-ohms/) of Time-Frequency department (www.femto-st.fr), and the MOSAIC group (https://teams.femto-st.fr/MOSAIC/) from MN2S department, at FEMTO-ST Institute.

The candidate will evolve in a group composed of researchers, engineers, technicians and will benefit from the support and skills of FEMTO-ST internal services (electronics/mechanics/computing), in an environment with access to a large number of instruments dedicated to time-frequency metrology and microfabrication platform (MIMENTO). The candidate will aim to present his/her work in regular group weekly meetings.

Contacts

Rodolphe Boudot, CNRS researcher
rodolphe.boudot@femto-st.fr
Phone: 03 81 40 28 56

Nicolas Passilly, CNRS researcher
nicolas.passilly@femto-st.fr
Phone: 03 63 08 26 24

Funded Internship / PhD offer

Location : Inria Saclay, Ecole Polytechnique, Palaiseau (Paris), France
Contact: Marc-Olivier RENOU (marc-olivier.renou@inria.fr)
Funded internship (~550€/month) & PhD

Quantum Distributed Computing

The basic situations in which Quantum Information Theory and quantum bits (qubits) of information allow for more efficient distributed algorithms than classical ones are mostly unknown. In particular, it is not known if:

1. quantum strategies outperform classical ones for the pragmatic synchronous distributed computing problem of finding a proper coloring of a loop of N processors. While the best classical solution is in time log*(N), the potential existence of a quantum solution in constant time is an open problem (arXiv:2403.01903, arXiv:2307.09444).
2. it is known that quantum strategies can speed up byzantine agreement protocols, yet no distributed quantum advantage allowing to tolerate more faulty processors is known (arXiv:2409.01707).

The project will be to study the limits of Quantum Information Theory for Distributed Computing. Several directions will be explored:

- Look for proof of existence or inexistence of quantum advantages in the local model, notably focusing one question 1 above.
- Look for proof of existence or inexistence of quantum advantages for byzantine agreements problems

Potential approaches (among many) are new methods using noncommutative polynomial optimization theory (related to Lasserre-Parrilo hierarchy) and C*/Operator algebras, and non convex/ML optimization tools to explore potential quantum strategies.

In case of continuation with a PhD, it may include collaborations with:

- Quantum Distributed Computing: Collaborations with Jukka Suomela (Aalto, Finland), Pierre Fraigniaud, Frédéric Magniez (Paris), Cyril Gavoille, Gilles Zémor (Bordeaux).
- Quantum Info Theory, Polynomial Optimization, C*/Operator Algebra: Nicolas Gisin (Geneva), Antonio Acin (Barcelona), David Gross (Cologne), Omar Fawzi (INRIA Lyon), Victor Magron (Toulouse), Igor Klep (Ljubljana)

In particular, the PhD could involve several 3-months long visits of the group of Jukka Suomela (Aalto, Finland).

Funded Internship offer

Location : Inria Saclay, Ecole Polytechnique, Palaiseau (Paris), France
Contact: Marc-Olivier RENOU (marc-olivier.renou@inria.fr)
Funded internship (~550€/month) & PhD

Quantum Info Theory: Quantum Networks

In 1964, John Stewart Bell proved that quantum physics is incompatible with our intuition that our world is local. More precisely, when two experimentalists measure the properties of two photons created by a same quantum source, they can produce correlations which cannot be explained by any classical theory. This was verified by famous experimental demonstrations, such as Aspect experiment, recently rewarded by a Nobel price. Those correlations, called quantum nonlocal correlations, are the fingerprint of quantum phenomena and at the origin of tremendous applications of quantum physics (Quantum Key Distribution, Quantum Random Number Generation, Device Independent Certification of Quantum devices, …).

A decade ago, physicists understood that Bell's theorem is the first elementary manifestation of a broader phenomenon called network nonlocality. When several quantum sources distributed in a network are measured in different nodes, certain correlations called quantum network nonlocal correlations may be created, that cannot be explained by classical physics.

The project is to understand quantum network nonlocal correlations, and to exploit them to either understand the foundations of physics or find practical applications to quantum theory (in randomness generation, cryptography, …). Depending on the profile of the candidate, several approaches can be considered: quantum information theory, mathematical physics, distributed computing, optimization, numerical, conceptual, … Some possible projects:

- Find generalization of the Bell theorem based on Network nonlocality concepts (see https://www.scientificamerican.com/article/quantum-physics-falls-apart-without-imaginary-numbers/, https://arxiv.org/abs/2105.09381)
- Understand the limits of quantum distributed computing (see https://arxiv.org/abs/2307.09444)
- Look for practical applications of network nonlocality for randomness generation, cryptography, … (see https://arxiv.org/abs/2104.10700, https://arxiv.org/abs/2209.09921)
- Understand the Navascués, Pironio, and Acín (NPA) hierarchy to improve the noise tolerance of existing theoretical results to make possible experimental realizations (see https://arxiv.org/abs/2201.05032, https://arxiv.org/abs/2011.02769)
- Understand the quantum inflation technic and look for its analytical convergence (see https://arxiv.org/abs/2210.09065)
- Find numerical methods to boost the inflation technic (see https://arxiv.org/abs/1609.00672)
- Other possibilities can be discussed.

I will guide the candidate in their choice of destination for a PhD. In case of continuation with a PhD, it may include collaborations with:

- Quantum Info Theory: Nicolas Gisin (Geneva), Antonio Acin (Barcelona), David Gross (Cologne), Omar Fawzi (INRIA Lyon)
- Quantum Distributed Computing: Jukka Suomela (Aalto, Finland), Pierre Fraigniaud, Frédéric Magniez (Paris)
- Polynomial Optimization, C*/Operator Algebra: Victor Magron (Toulouse), Igor Klep (Ljubljana)

Master thesis proposal

Institut des Nanosciences de Paris
Sorbonne Université, 4 place Jussieu, Paris

Title: Quantum dot fluorescence and optomechanical coupling

Keywords: fluorescence, plasmonics, laser

Scientific description: The emission of colloidal quantum dots is highly dependent on their environment. Placed between two layers of gold, and excited in UV light, their emission couples with surface plasmons and its dynamics is accelerated. The smaller the gap between the two gold layers, the more the emission is modified. We propose to actively modify the spacing between the two layers in order to modify quantum dot emission.

We will use the transient grating method, which involves exciting the sample with two infrared laser beams (λ_{exc} =1064nm; 30ps pulse duration) to produce interference bangs with a period Λ. Through photoelasticity, the standing waves thus created cause the sample to vibrate, modulating its thickness.

The aim of the internship will be to study how the acoustic wave thus created modifies the properties of the light emitted.

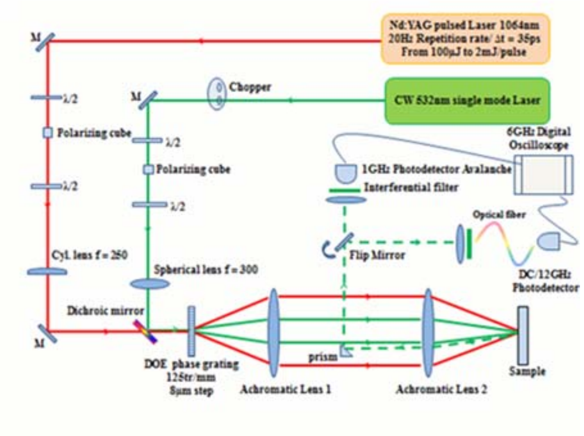


Figure 1 Scheme of the experiment. M (Mirror), DOE (Diffractive Optical Element), λ/2 (half wave plate)

The first step will be to produce the samples. After depositing an optically thick layer of gold on a glass subtrate, a solution of CdSe/CdS quantum dots will be deposited. This emitter layer is then covered by a thin layer of gold. Secondly, this layer will be optically characterized under a microscope, both to characterize its thickness in white light and the fluorescence of the quantum dots under UV illumination. Finally, we'll use the transient grating method to change the thickness of the sample. Both thickness and quantum dot fluorescence will be studied.

Techniques/methods in use: fluorescence, microscopy, spectroscopy

Applicant skills: optics, nanosciences, taste for experiments

Internship supervisors:

Agnès Maître, agnes.maitre@insp.upmc.fr, 01 44 27 42 17

Olga Boyko—Kazymyrenko, Olga.Boyko@insp.jussieu.fr, 01 44 27 45 33

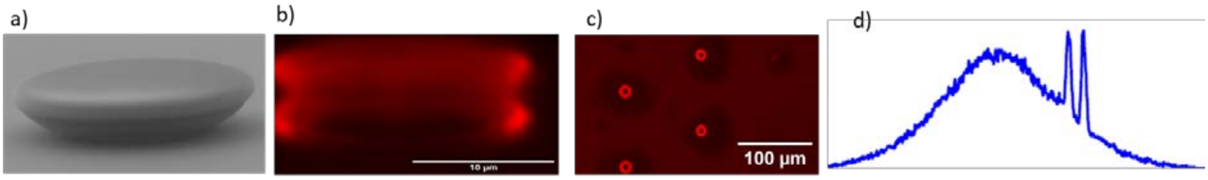
Internship location: INSP, Sorbonne université, Jussieu, Tour 22-32, 3-5th floor

Possibility for a Doctoral thesis: N

Title: Excitonic whispering gallery mode laser in high pumping regime

Keywords: laser, quantum dot, whispering gallery mode, exciton

Scientific description:
In nanophotonics and quantum technologies, photon sources are a ressource which can be integrated into a chip. Cylindrical dielectric microdisks make excellent resonators in which optical gallery modes can propagate at the air/dielectric interface.
Using optical lithography, we have fabricated gallery-mode resonators on which we have deposited fluorescent nano-emitters, colloidal quantum dots. These are CdS/CdSe/CdS semiconductors in a spherical core/shell/shell configuration. Of nanometric dimensions, their fluorescence wavelength depends on their size. They can emit single photons, are resistant to photobleaching and are bright under strong excitation. We have deposited these quantum dots in high concentration on microdisks, and excited them with a green laser. The excitons thus created enabled us to achieve a significant gain. We were therefore able to create gallery modes excitonic microlasers. [1].



a) microdisk optical cavity C b) Fluorescent gallery mode (side view split by substrate reflection) c) Gallery mode (top view) d) Laser mode and fluorescence spectra

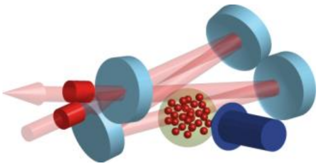
The aim of this internship will be to study these gallery-mode lasers, and to understand their characteristics as a function of their size, of the excitation when it is close to the laser threshold or more higher... In particular, we will be interested in the behavior of these lasers far from the threshold, when the excitation laser is intense. Under these conditions, the resonant gallery mode intensity is high. If if coupling to the excitons is sufficiently strong, emission will be modified by exciton-photon interaction. We will study these strong coupling configurations in relation to theoretical predictions.
[1] C. Kersuzan et al, *ACS Photonics, 11(4), 1715-1723 (2024)*

Techniques/methods in use: fluorescence, microscopie, spectroscopie
Applicant skills: optics and/or nanophotonics

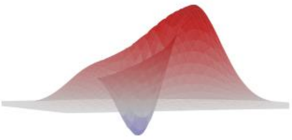
Internship supervisor(s): Agnès Maître, agnes.maitre@insp.upmc.fr, 01 44 27 42 17
Internship location: INSP, Sorbonne université, Jussieu, Tour 22-32, 5th floor

Possibility for a Doctoral thesis: Y , funding : Doctoral school

Quantum engineering of light with intracavity Rydberg superatoms



Internship, PhD & Post-Doc offers



Quantum Photonics Team,
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https://jeipcdf.cnrs.fr/quantum-photonics/

Optical photons are excellent carriers of quantum information, but their lack of mutual interactions is a major roadblock for quantum technologies. We enable such interactions by transiently injecting the photons into an intra-cavity cold atomic gas and converting them into strongly interacting Rydberg polaritons. The Rydberg-blockaded cloud then acts as an effective two-level superatom with an enhanced coupling to light. We can coherently manipulate its state, efficiently detect it, and observe state-dependent π phase flips on the light reflected from the cavity as required for many quantum engineering tasks [1]. Recently, we obtained the first fully deterministically generated free-propagating states of light with negative Wigner functions [2]. This platform opens many perspectives for developing deterministic multi-photon gates, performing quantum measurements impossible with current techniques, generating non-classical free-propagating resource states, and studying strongly correlated quantum fluids of light.

We recently expanded the capabilities of this platform towards the multi-superatom regime, to perform deterministic multi-photon quantum logic and generate complex Wigner-negative states of light. Post-doc, PhD, and internship positions are open on this project.

We are also looking for a post-doc, a PhD student and interns to assist us in the design and construction of a new setup where single atoms will be trapped and controlled next to a superatom. The industry-connected research project will aim at developing quantum interconnects between static and flying qubits, in a collaboration with the quantum tech company Pasqal.

Both projects require a background in quantum physics, cold atoms and quantum optics, an interest in experimental research and an ability to work in a team.

[1] J. Vaneecloo, S. Garcia & A. Ourjoumtsev, Phys. Rev. X **12**, 021034 (2022)

[2] V. Magro, J. Vaneecloo, S. Garcia & A. Ourjoumtsev, Nature Photonics 17, 688 (2023)

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🖃 : Daniel.Comparat@cnrs.fr

Internship/PhD/post doc offer 2024/2025

Laboratory: Aimé Cotton (LAC)
Director: Olivier Dulieu
Address: bâtiment 505, campus d'Orsay, 91405 Orsay
Person in charge of the internship: Daniel COMPARAT
Tel: 06 79 76 86 19
e-mail: daniel.comparat@cnrs.fr

Electron Electric Dipole Moment using Cs in cryogenic matrix

Scientific project: Electron Electric Dipole Moment using Cs in cryogenic matrix

Electric Dipole Moments (EDMs) of electrons, neutrons or nuclei are sensitive probes for new physics beyond the Standard Model of particle physics. In the present project (EDMMA: Electric Dipole Moment with atoms and molecules in Matrix), we propose to measure the electron EDM using embedded particles in a cryogenic solid matrix of rare gas or hydrogen. Matrices offer unprecedented sample sizes while maintaining many characteristics of an atomic physics experiment, such as manipulation by lasers. An EDM experiment on atoms and molecules in inert gas matrices has the potential to reach a statistical sensitivity in the order of 10-36e.cm; a value several orders of magnitude beyond that of any other proposed technique. In a strong collaboration between experimental (LAC, ISMO,LPL) and theoretical (CIMAP) groups, we seek to perform a detailed investigation of all limiting effects (trapping site dependence of optical pumping and coherence times mainly) using metal atoms (Cs typically) in argon and parahydrogen matrices in view of a first proof of principle EDM measurement. This will pave the way toward unprecedented sensitivity. During this work, that can be a Internship PhD or post doc we propose to setup the cryostat with argon and make the first test of RF spin dynamics and hyperfine structure study of cesium embedded in an argon matrix. In the same time collborations with US colleague at Reno undeer an ANR/NSF grant called Quantum sensing in cryocrystals for fundamental physics (QUIC) will start.

Methods and techniques: spectroscopy, cryogeny, laser, RF, fundamental physics

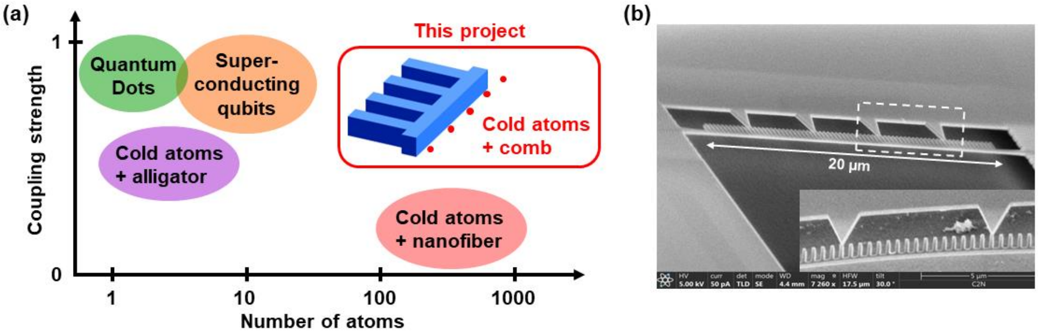
Internship (Master 2)/PhD offer

Atom-photon interactions with a nanostructured waveguide supporting exotic dispersions: collective properties and applications to waveguide QED

Laboratory: Laboratoire Charles Fabry and Laboratoire Lumière Matière et Interfaces
Contact: Nikos Fayard (nikos.fayard(at)ens-paris-saclay.fr)
Christophe Sauvan (christophe.sauvan(at)institutoptique.fr)
Keywords: Quantum optics, Nanophotonics, Waveguide QED, Photonic crystals, Slow light
Possibility to go on with a PhD: Yes
Funding: ANR project (funding secured)

This internship/PhD project stands at the interface between Quantum Optics and Nanophotonics. It is part of a collaboration between Laboratoire Lumière, Matière et Interfaces (Lumin, ENS Paris-Saclay) and Laboratoire Charles Fabry (LCF, Institut d'Optique).

Achieving strong light-matter interactions at the single photon level is a long-standing goal of both fundamental and technological importance. Many recent works have studied **cavity-free systems, based on single-pass configurations**. In this context, **the atom-photon interaction can be increased by using sub-wavelength, nanostructured, waveguides** that confine the electromagnetic field to deeply subwavelengths scales in the transverse directions. This is the emerging field of **waveguide QED**, with two important figures of merit. First, the coupling strength between atoms and guided photons is quantified with the β factor, which represents the fraction of the decay rate that is funneled into the guided mode. A second relevant figure of merit is the number of atoms N that can be coupled together to the waveguide. **Currently, no system can provide both many atoms $N \geq 100$ and a high coupling strength $\beta \geq 0.9$.**



(a) Positioning of the project. (b) SEM picture of a comb waveguide (Centre de Nanosciences et de Nanotechnologies, C2N).

Recently, we have designed a new waveguide geometry, the asymmetric comb waveguide. Thanks to a well-designed transverse symmetry breaking, the asymmetric comb mitigates the weaknesses of existing structures and opens new perspectives. This new waveguide geometry should allow to reach experimentally the high β – high N regime in order to realize quantum operations on propagating photons. **Moreover, the impact of the waveguide dispersion $\omega(k)$ on the collective properties of the atomic ensemble is still unexplored. The objective of the PhD is to explore the role of the waveguide dispersion in the building of the collective properties of an ensemble of atoms coupled to a slow-light photonic-crystal waveguide.**

The study will rely on **theory and numerical calculations (classical and quantum electrodynamics, nanophotonics)**. The internship and its extension into a PhD thesis will take place within the framework of an ANR-funded project.

SCIENCES SORBONNE UNIVERSITÉ

LKB

Master thesis proposal

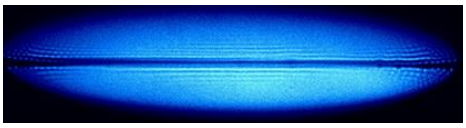
Laboratoire Kastler Brossel, 4 place Jussieu
75005 Paris
Director: Antoine Heidmann

Title: Probing fundamental physics with H_2^+

Keywords: proton to electron mass ratio, fundamental constants, trapped ions, quantum logic, laser, frequency comb, spectroscopy

Scientific description:

Context: Numerous precision experiments are being carried out to probe the Standard Model of physics, with two objectives: (i) to improve knowledge of the fundamental constants in the frame of CODATA organization and (ii) to test new physics beyond the standard model.
Hydrogen molecular ions (H_2^+ or HD^+) are among the simplest molecular species. They are made of three particles, two nuclei and one electron. They are amenable to high precision energy level and transition frequency calculations with up to 12 significant digits (1 ppt) [Karr17]. Transition frequencies are particularly sensitive to the proton to electron mass ratio $\mu=m_p/m_e$, which start being improved thanks to new measurements performed on HD^+ ions [Patra20,Alighanbari23]. The relative inaccuracy on μ presently reaches about $2.\ 10^{-11}$ [Delaunay2023]. It can be further improved using H_2^+ ions.
LKB Experiment: H_2^+ ions are trapped and sympathetically cooled to mK temperatures using sympathetic cooling by laser cooled Be^+ ions. The image shows a Coulomb crystal of laser cooled Be^+ ions observed through resonance fluorescence at 313 nm. The dark line in the center is due to the presence of H_2^+ ions [Schmidt20].



The intern and PhD work will consist in

- Performing H_2^+ **spectroscopy** using a 9.17 µm quantum cascade laser referenced to the Système International to give a new determination of μ using the experiment we have developed.
- Working out how quantum logic protocols can be adapted to the specific case of H_2^+ to push further the resolution and analyze time variation of fundamental constants.

CODATA: https://pml.nist.gov/cuu/Constants/
[Delaunay2023] C. Delaunay, J.-Ph. Karr et al., Phys. Rev. Lett. **130**, 121801 (2023)
[Karr17] J.-Ph. Karr, L. Hilico, V.I. Korobov, Phys. Rev. A **95**, 042514 (2017)
[Patra20] S. Patra et al. Science **369**, 1238 (2020)
[Alighanbari23] S. Alighanbari et al. Nature physics **19**, 1263 (2023)
[Schmidt20] J. Schmidt, …, L. Hilico, Phys. Rev. Applied **14**, 024053 (2020).

Team : Jean-Philippe Karr, Laurent Hilico
PhD : Maxime Leuliet PhD
Postdoc : Hugo Nogueira Demattos, Maen Salman
Collaborations
VU Amsterdam, PIIM Marseille, SYRTE Paris,

Techniques/methods in use:

Applicant skills: Experimental, ultrastable lasers, ion trapping, remote control, data analysis
Industrial partnership: N

Internship supervisor(s): Laurent Hilico, Laurent.hilico@upmc.fr, 01 44 27 60 79
Internship location: LKB, T13, 4 place Jussieu, Paris

Possibility for a Doctoral thesis: Yes, EDPIF funding competition

Sorry, we are not available on 3 octobre for the LKB visit. Visit us at any time

Internship Offer (M2) – Generating nonclassical states of light using waveguide quantum electrodynamics

We are seeking a motivated and talented **Master's (M2) student** for a research internship focused on **theoretical quantum optics**. The internship will involve exploring the interaction between a laser field and a quantum emitter to calculate the quantum photonic states that can be generated through this interaction.

Overview

Title: Generating nonclassical states of light using waveguide quantum electrodynamics
Institution: Sorbonne University - Ecole Normale Supérieure - CNRS - Laboratoire Kastler Brossel
Team: Nanophotonics team - Hanna Le Jeannic, Alberto Bramati, Quentin Glorieux
Location: Jussieu campus. Paris, France
Duration: 4-6 months
Deadline for applications: December
Websites: www.quantumoptics.fr and www.lejeannic.quantumoptics.fr/

Project Overview:

Photons have long been favored as information carriers due to their non-interacting nature. Traditionally, atoms have been the primary means to manipulate and process quantum information carried by photonic qubits. However, recent groundbreaking advancements in solid-state emitters such as color centers, quantum dots, and molecules have ushered in a new era of highly coherent interaction with light, akin to atomic-level interactions and enable to completely reshape few photon pulses [1].

If so far most of the effort in the solid-state has been towards the generation of single photons, recent proposals suggest that the interaction of light with a single two-level emitter could also produce highly nonclassical states when coupled to photonic waveguides[2, 3].

This internship will focus on studying the evolution of quantum states when a few photons (e.g., from a weak laser) interact with a two-level quantum emitter (atom, molecule, or quantum dot), which is critical for quantum computing, communication, and sensing. We aim to model realistic systems (e.g., imperfect emitters or couplings) and explore how varying interaction parameters (detuning, input field) might generate nonclassical states like squeezed states or even cat or GKP states, and under what conditions this can be achieved.

The project will involve:

- Modeling and simulating the interaction between a few photon field and quantum emitters using a recently developed approach. [2]

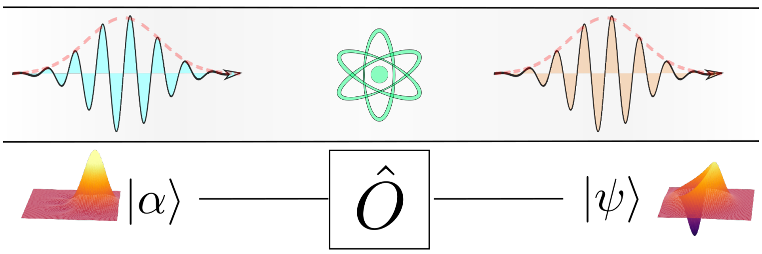


Figure 1: Concept idea: a few photon coherent state (i.e. an attenuated laser) interacts with a quantum emitter in a waveguide and enable the creation of a nonclassical quantum state, with a Negative Wigner function.

- Investigating how different parameters (detuning, coupling, decoherence) affect the quantum states produced.
- Propose an experimentally viable approach to generate interesting quantum states of light using single solid states emitters in a nanophotonic waveguide.

This work will contribute to a better understanding of quantum state manipulation, a fundamental topic in advancing quantum technologies.

Key Responsibilities:

- Perform theoretical analysis and calculations.
- Develop and implement computational models for simulating quantum interactions.
- Analyze and interpret the results in the context of quantum state generation.
- Collaborate with the research team and contribute to group discussions.
- Document findings and potentially contribute to academic publications.

Candidate Profile:

- Currently enrolled in a **Master's program (M2)** in **Quantum Mechanics**, **Optics**, or a related field.
- Familiarity with **quantum optics** and/or **quantum information** is a plus.
- Experience with **computational tools** (in particular Python).

Benefits:

- Hands-on experience in cutting-edge research in quantum physics.
- Possibility to contribute to scientific publications.
- Possibility of going on in Ph.D (experimental)

Application:

For inquiries or more information about this internship or to apply for this internship, don't hesitate to get in touch with us directly at hanna.le-jeannic@cnrs.fr. Please submit your CV, a brief cover letter explaining your interest in the position, and your academic transcripts.

Nanophotonics group at LKB

We are a group of friendly and welcoming scientists and we aim to create **an inclusive and supportive research environment.** We strongly believe in the value of diversity and inclusion in the field of quantum physics and we encourage **women and/or individuals from underrepresented minority groups** to apply for this internship.

We look forward to receiving your application!

References

[1] H. Le Jeannic, A. Tiranov, J. Carolan, T. Ramos, Y. Wang, M. H. Appel, S. Scholz, A. D. Wieck, A. Ludwig, N. Rotenberg, L. Midolo, J. J. García-Ripoll, A. S. Sørensen, and P. Lodahl, "Dynamical photon-photon interaction mediated by a quantum emitter," *arXiv*, Dec. 2021.

[2] A. H. Kiilerich and K. Mølmer, "Quantum interactions with pulses of radiation," *Phys. Rev. A*, vol. 102, p. 023717, Aug. 2020.

[3] K. Kleinbeck, H. Busche, N. Stiesdal, S. Hofferberth, K. Mølmer, and H. P. Büchler, "Creation of nonclassical states of light in a chiral waveguide," *Phys. Rev. A*, vol. 107, p. 013717, Jan. 2023.

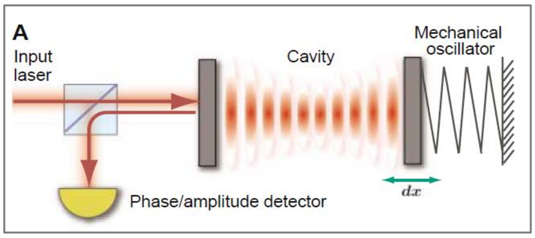
Internship, Phd & Post-Doc offers
Optomechanics and quantum measurements group
Laboratoire Kastler Brossel

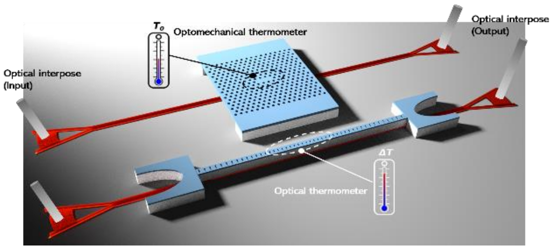
Sorbonne université
4 place Jussieu, 75005 Paris
tristan.briant@lkb.upmc.fr, stephan.briaudeau@lecnam.net, olga.kozlova@lne.fr

Title: Quantum correlation thermometry below 300 K

Since 2019, the kelvin unit is defined by the value of the Boltzmann constant. Usual primary thermometry uses equation of state to link the temperature to another physical quantity (gas pressure, speed of sound in a gas, voltage noise of an electrical resistor..). Yet, only one experimental demonstration of the quantum measurement of thermodynamic temperature has been achieved by Purdy et al. at NIST in 2017.

The aim of this project is to demonstrate and validate innovative primary temperature sensors using quantum technologies that can either work from low temperature near the quantum regime of up to room temperature. The correlation of both thermal and quantum fluctuations of a mechanical resonator allows to scale the size level of thermal motion in term of quantum energies determined by Planck’s constant and can extend quantum primary thermometry up to room temperature.





The aim of this Phd thesis is to demonstrate the potential of quantum optomechanics for the determination of thermodynamic temperature, from the quantum regime (at cryogenic temperature, below), up to room temperature, using quantum correlation technique. This project aims at developing optomechanical sensors for nanoscale and quantum temperature metrology. Our team has already demonstrated optomechanical noise thermometry from 4K to 300 K, with a nanobeam. In addition, a “2D” geometry will be tested while it will be engineered for better thermal dissipation.

The PhD will take place mainly in LKB where the quantum readout will be developed in the Optomechanics and Quantum Measurements team of LKB in collaboration with the clean-room facilities housed by C2N which has a thorough knowledge of the fabrication of photonics and phononics crystals. Finally, CNAM and LNE will develop methods for the metrological validation of the optomechanical thermometer, and its traceability to the International Temperature Scale.

Key words: experimental work, quantum physics, laser, cryogeny, micro and nano fabrication, clean room, metrology

Briant T et al. « **Photonic and Optomechanical Thermometry. Optics 2022, 3, 159-176.** »

Title: Attosecond control of non-classical states of light

Keywords: quantum optics, attosecond photonics, high harmonic generation, semiconductors

Scientific description:
High-harmonic generation is a light up-conversion process occurring in a strong laser field, leading to coherent attosecond bursts of extreme broadband radiation. As a new paradigm, attosecond electronic or photonic processes such as high-harmonic generation (HHG) can potentially generate non-classical states of light well before the decoherence of the system occurs. This could address fundamental challenges in quantum technology such as scalability, decoherence or the generation of massively entangled states with ultrafast processing. We recently reported experimental evidence of the non-classical nature of the harmonic emission in several semiconductors excited by a femtosecond infrared laser (Theidel et al, submitted to Nature, in review, pdf on demand). By investigating single- and double beam intensity cross-correlation, we observe two-mode squeezing in the generated harmonic radiation, which depends on the laser intensity that governs the transition from Super-Poissonian to Poissonian photon statistics. The measured violation of the Cauchy-Schwarz inequality realizes a direct test of multipartite entanglement in high-harmonic generation. These pioneer experiments were realized with a train of attosecond pulses but without the control of the intra-optical cylcle of the light. The project will consist in realizing a platform that will allow controlling the carrier to envelope phase (CEP) of the laser that drives the semiconductor HHG emission. The CEP of the laser will allow controlling the non-classical state of the single photon emission, in connection with our recent finding in the intensity control of the HHG light states (Theidel et al.)
In conclusion, HHG is a new quantum bosonic platform that intrinsically produces non-classical states of light with unique features such as multipartite broadband entanglement or multimode squeezing. The source operates at room temperature using standard semiconductors and a standard commercial fiber laser, opening new routes for the quantum industry, such as optical quantum computing, communication and imaging. The attosecond control of light states open the vision of quantum processing on unprecedented timescales, an evident perspective for future quantum optical computers.

Techniques/methods in use: quantum states detection, attosecond light control
Applicant skills: Quantum optics, ultrafast laser optionnally. **Industrial partnership**: Y

Supervisor: Hamed Merdji, hamed.merdji@polytechnique.edu
Internship location: LOA, ENSTA/Ecole Polytechnique, Palaiseau.

INSTITUT
POLYTECHNIQUE
DE PARIS

Ultrafast Quantum
Optics Group

LOA, ENSTA,
Ecole Polytechnique. Palaiseau
Director: Stéphane Sebban

Title: Quantum imaging with non-degenerated entangled photons

Keywords: quantum optics, high harmonic generation, imaging

Scientific description:
Quantum imaging (QI) is a rapidly developing field of research with stunning progresses and emerging societal applications. Quantum-enhanced imaging schemes harness the beneficial properties of entangled photon pairs allowing transferring amplitude and phase information from one photon state to the other. The technique is however still in its infancy and we propose to go beyond the state of the art. The main goal is to develop advanced QI protocols that exploits photon pairs at extreme wavelengths from telecom to the visible down to the deep UV using a non-classical source based on high harmonic generation (HHG). The main objective of the project will consist in using a pair of non-degenerated entangled photons at 2 harmonics from the HHG frequency comb to perform a quantum imaging experiment in the far field regime. We will study the possibility of transferring the sensing and resolution benefit from one spectral range to another one. Indeed, an intriguing question is about the spatial resolution achievable in the QI scheme, especially in the case of non-degenerate photon pairs. Interestingly, recent theoretical studies [Li17,Asb19] predict that, in the quantum diffractive imaging regime, radiation damage-free coherent diffraction can be achieved with spatial resolution limited by the shortest wavelength by using entangled photons from near infrared to deep-UV.

The quantum correlations between the two photons from the same harmonic generation process will be used to transfer amplitude and phase information between the two photons. In the diffractive regime, and in a "ghost diffractive imaging" configuration based on the coincident detection of the two entangled photons, it is a priori possible to obtain a resolution related to the UV photon, i.e. in the sub-µm range. Ultimately, the candidate will investigate novel protocols to create high-resolution label-free images of complex structures (e.g. cells) embedded inside biological tissues [Zhang23].

References:
[Asb19] Asban, S. et al., PNAS 116, (24) 11673 (2019)
[Li17] Li, Z. et al., J. Phys.B: AMOP 51 (2) 025503 (2017)
[Zhang23] Zhang, Y., et al., arXiv:2303.05643 (2023)

Techniques/methods in use: quantum imaging, HHG, femtosecond mid-infrared laser
Applicant skills: Quantum optics. **Industrial partnership**: Y

Supervisor: Hamed Merdji, hamed.merdji@polytechnique.edu
Internship location: LOA, ENSTA/Ecole Polytechnique, Palaiseau.

Master 2 offer / PhD offer (ANR Funded)

Post: Master 2 internship and PhD student position
Location: Laboratoire de Physique des Lasers (LPL), CNRS-Univ Sorbonne Paris Nord, Villetaneuse, France
Team: Interferometry and optics for atoms (https://www.lpl.univ-paris13.fr/en/research/interferometry-and-optics-for-atoms-oia/).
Advisor: Quentin Bouton (quentin.bouton@univ-paris13.fr)
Gabriel Dutier (gabriel.dutier@univ-paris13.fr)
Nathalie Fabre (nathalie.fabre@univ-paris13.fr)

Casimir-Polder interaction control of cold atoms and nano devices for fundamental physics

A striking feature of quantum mechanics is the possibility of energy change ΔE during a time Δt due to the Heisenberg principle ($\Delta E \Delta t \geq \hbar/2$). It leads to quantum fluctuations that create virtual photons and generate a quantized field. In particular, the presence of boundaries, given for example by a surface and an atom, modifies this field. It results in a force between the surface and the atom, known as the Casimir-Polder (C-P) force. This force becomes preponderant at the nanoscale and thus plays a major role in a multitude of areas of Physics, ranging from atomic physic to theoretical fundamental physics such as the 5th force and accurate gravity measurement.

Despite its simplicity, combined with strong scientific and technological interests, C-P interaction, at its fundamental level, remains largely unexplored mainly due to challenges associated with precise control of the atom-surface distance and knowledge of the surface characterization. In this context, our team has built a slow atomic beam interacting with a nanograting [1,2]. This jet interacts with a carefully self-engineered nanograting, leading to a diffraction pattern dominated by the C-P force. This unique configuration allows us to study precisely the C-P interaction.

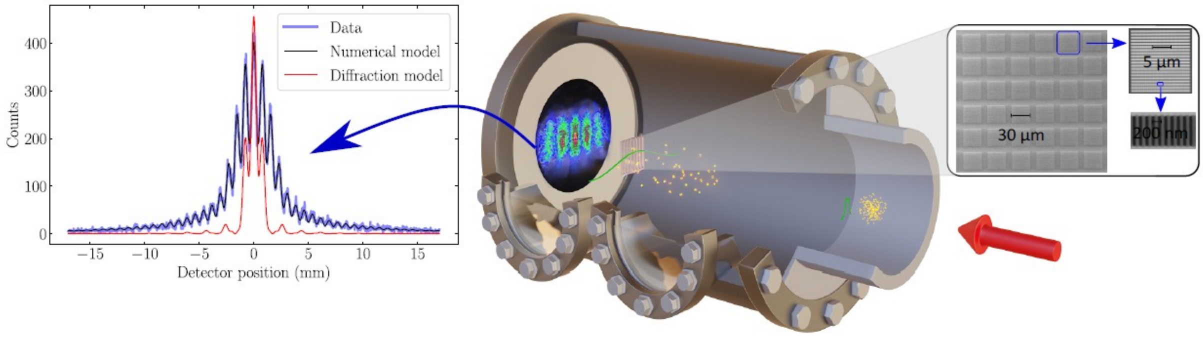


Figure. Sketch of the team's experiment, in which a cold atom source containing neutral Argon is optically pushed towards a nanograting. The atoms thereupon interact with the nanograting within the C.P potential, resulting in a diffraction pattern. A typical measured diffraction pattern is shown on the left in blue. The experimental signal is mainly influenced by the C.P interaction, as underlined by the expected diffraction pattern without the C.P potential shown in red. On the right is an image of typical manufactured nanogratings used in the experiment.

The current interest of the experiment is to achieve an in-depth understanding of the C-P interaction. To achieve this goal, the successful applicant will take an active role in various aspects of the experiment including **data acquisition, data analysis**, the development of tools for characterizing the atomic source, and the installation of an **optical dipole trap** (to increase the atomic flux and reduce the atomic velocity). Additionally, the internship has as well a **theoretical component with the description of the interference figure and quantum electrodynamic calculations**. According to the candidate's preferences, there may also be a clean-room aspect to the internship, involving work on the generation of new nanogratings. The short term goal of the project is to tailor the C-P interaction using material geometries. In the medium term, this work will open the door to study eventual modifications of the Newtonian gravitational interaction at short range, where C-P interaction shields such forces.

The successful applicant will work as a fully integrated team member. The internship encompasses various components, including experimental work, cleaning room activities, and theoretical studies, which we can be arranged to suit the applicant's preferences. **The master's internship is scheduled to begin in spring 2025, and it can be followed by a PhD thesis funded by ANR, starting in September 202**5.

[1] C. Garcion, et al. *Phys. Rev. Lett*. **127**, 170402 (2021).
[2] J. Lecoffre et al, *arXiv:2407.14077* (2024).

LPL
Laboratoire de
physique des lasers

Post: **Master Internship in Ultra-precise Mid-Infrared Molecular Spectroscopy**
Location: Laboratoire de Physique des Lasers, CNRS-Université Sorbonne Paris Nord Villetaneuse, France
Team: Metrology, Molecules and Fundamental Tests
Supervisors: Dr Mathieu Manceau (mathieu.manceau@univ-paris13.fr)
Dr Benoît Darquié (benoit.darquie@univ-paris13.fr)
Contract: 4-6 months, starting in spring 2025

Looking for potential variations of the proton-to-electron mass ratio and other tests of fundamental physics via precision measurements with molecules

Internship Description:
The master student will participate in cutting-edge experiments aimed at ultra-precise measurements of rovibrational molecular transitions and dedicated to measuring/constraining the potential time variation of the proton-to-electron mass ratio (**μ**), a fundamental constant of the standard model (**SM**). Such variations, if detected, would be a signature of physics beyond the SM, providing insights into the nature of dark matter and dark energy. The idea here is to compare molecular spectra of cosmic objects with corresponding laboratory data. The experimental setup is based on quantum cascade lasers (**QCLs**) locked to optical frequency combs, with traceability to primary frequency standards, a breakthrough technology developed at Laboratoire de Physique des Lasers (**LPL**), allowing unprecedented spectroscopic precision in the mid-infrared range.

This internship will focus on measuring mid-infrared molecular transitions of **methanol** (**CH_3OH**), a molecule known for its enhanced sensitivity to changes in μ. The student will set up and stabilize a new QCL in a spectral region hosting particularly relevant transitions. The work will involve achieving sub-Doppler spectroscopic resolution to reach target laboratory frequency accuracies of ~100 Hz needed for **comparisons with astronomical observations**. This activity is part of the **ANR Ultiμos project**, a collaborative effort which seeks to refine current constraints on the possible variation of μ which involves leading research institutions, including **Laboratoire Kastler Brossel (LKB, L. Hilico)** and **MONARIS (C. Janssen)** at Sorbonne Université. The three partners of the Ultiμos consortium will collaborate to conduct measurements in methanol and other species such as ammonia (NH_3) in different spectral windows, to identify transitions as targets for future Earth/space comparison campaigns, which could further tighten constraints on variations of μ. Other collaborators, such as **Vrije Universiteit Amsterdam** and **Onsala Space Observatory**, will provide theoretical and observational/astronomical support to complement the experimental efforts.

The proposed laser technology is also crucial for the ongoing development at LPL of **a new-generation molecular clock** specifically designed for precision vibrational spectroscopy of **cold polyatomic molecules**. The student may therefore be involved in first precise spectroscopic measurements on cold molecules produced at ~1 K in a novel cold molecule apparatus. Combining frequency metrology and cold molecule research as the potential to bring even more stringent constraints on a drifting-μ, and opens possibilities for using polyatomic molecules to perform other fundamental tests, including the measurement of the energy difference between enantiomers of a chiral molecule, a signature of **parity (left-right symmetry) violation**, and a sensitive probe of dark matter.

Keywords: fundamental constants, standard model, precision measurements, ultra-high-resolution spectroscopy, frequency metrology, quantum cascade lasers, frequency comb lasers, cold molecules, molecular physics, quantum physics, astrophysics, optics & lasers, vacuum, electronics, programming & simulation

Relevant publications from the team: Tran *et al*, APL Photonics 9, 3, (2024); Fiechter *et al*, J Phys Chem Lett **13**, 42 (2022); Santagata *et al*, Optica **6**, 411 (2019); Cournol *et al*, Quantum Electron. **49**, 288 (2019), arXiv:1912.06054; Tokunaga *et al*, New J. Phys. **19**, 053006 (2017); Argence *et al*, Nature Photon. **9**, 456 (2015), arXiv:1412.2207.

Requirements: The applicant should be doing its master studies in a relevant area of experimental physics or chemical physics: atomic, molecular and optical physics, spectroscopy, lasers, quantum optics. Interested applicants should email a CV, a brief description of research interests and the contact details of 2 referents to M. Manceau (mathieu.manceau@univ-paris13.fr) and/or B. Darquié (benoit.darquie@univ-paris13.fr).

Funding is already secured for a potential PhD following the internship.

Master 2: *International Centre for Fundamental Physics*

PhD PROPOSAL

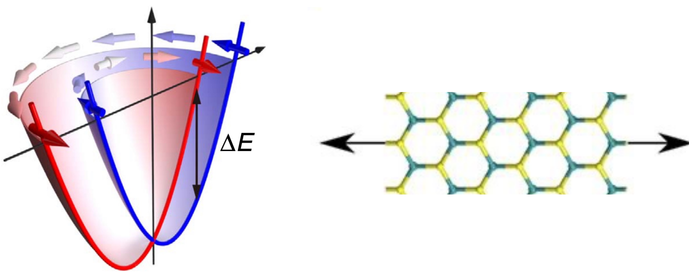
Laboratory name: Laboratoire de Physique du Solide
CNRS identification code: UMR 8502
Internship director'surname: TEJEDA
e-mail: antonio.tejeda@cnrs.fr
Phone number: 01 69 15 47 07
Web page: https://equipes2.lps.u-psud.fr/antonio-tejeda-2/
Internship location: Orsay
Thesis possibility after internship: YES
Funding already obtained for a PhD: NO If YES, which type of funding:

Spin-orbit coupling tuning in two-dimensional systems

Next generation spintronics efficiently targets ultra-low power memories for green electronics and on a longer term full-spin information processing. The spin-orbit coupling (SOC) plays a fundamental role in spintronics as it allows controlling the spin in the conduction channels through an electrostatic manipulation [1-3].

SOC is greatly enhanced at reduced dimensions since the inversion symmetry is broken at surfaces or interfaces, and the resultant electric field couples to the spin of itinerant electrons, a phenomenon known as Rashba effect. Spin-orbit coupling is being intensively studied in two dimensional systems as in transition metal dichalcogenides, hybrid perovskites or in molecular layers on ferromagnetic substrates [4-6].

In this internship, we will tune the SOC in 2D materials by structural modification, for instance by introducing defects in the structure (vacancies or impurities) or by introducing strain in the lattice. The effect of the induced structural modification will be studied by electron diffraction and the impact on the electronic bands will be determined by angle-resolved photoemission (occupied states) and by spin- and angle-resolved inverse photoemission (unoccupied states) [7].



(Left) Spin-orbit splitting of the bands due to Rashba effect. (Right) Strain in 2D materials is a way of tuning the spin-orbit coupling.

Profile: Experimentalist with solid state formation. Experience in surfaces physics, electron spectroscopies, local microscopies or diffraction will be appreciated. Ability to work in a team.

[1] A. Fert, "Nobel Lecture: Origin, development, and future of spintronics", Rev. Mod. Phys. 80, 1517 (2008).
[2] H. C. Koo, J. H. Kwon, J. Eom, J. Chang, S. H. Han, and M. Johnson, "Control of Spin Precession in a Spin-Injected Field Effect Transistor", Science 325, 1515 (2009).

[3] A. Soumyanarayanan, N. Reyren, A. Fert and C. Panagopoulos, “Emergent Phenomena Induced by Spin–Orbit Coupling at Surfaces and Interfaces”. Nature 539, 509 (2016)

[4] D.W. Latzke W. Zhang, A. Suslu, T.-R. Chang, H. Lin, H.-T. Jeng, S. Tongay, J. Wu, A. Bansil, and A. Lanzara, “Electronic structure, spin-orbit coupling, and interlayer interaction in bulk MoS2 and WS2”, Phys. Rev. B 91, 235202 (2015).

[5] J. Even, L. Pedesseau, J.-M. Jancu, and C. Katan, “Importance of Spin−Orbit Coupling in Hybrid Organic/Inorganic Perovskites for Photovoltaic Applications”, J. Phys. Chem. Lett. 4, 2999 (2013).

[6] C. Barraud, P. Seneor, R. Mattana, S. Fusil, K. Bouzehouane, C. Deranlot, P. Graziosi, L. Hueso, I. Bergenti, V. Dediu, F. Petroff and A. Fert., “Unravelling the role of the interface for spin injection into organic semiconductors”, Nature Phys. **6**, 615 (2010).

[7] A. F. Campos, P. Duret, S. Cabaret, T. Duden, A. Tejeda, “Spin- and angle-resolved inverse photoemission setup with spin orientation independent from electron incidence angle”, Rev. Sci. Instrum. 93, 093904 (2022).

Please, indicate which speciality(ies) seem(s) to be more adapted to the subject:

Condensed Matter Physics: YES
Soft Matter and Biological Physics: NO
Quantum Physics: YES
Theoretical Physics: NO

PhD/M2 internship Position in Experimental Condensed Matter Physics

---

Spectroscopy of Quantum Spin Liquids in Frustrated Magnets

Information

3-years PhD funded by CNRS

Joint PhD program (co-tutelle possible, not mandatory): *Université Paris-Saclay (France) & Université de Sherbrooke (QC, Canada)*

Laboratoire de Physique des Solides UMR8502 / Département de Physique Université de Sherbrooke

Doctorate school: *École doctorale Physique en Ile de France EDPIF*

PhD supervisors: Edwin KERMARREC / Jeffrey QUILLIAM

Period: October 1st, 2025 to September 30th, 2028 (PhD) / ~1st semester 2025 (M2 internship)

PhD/M2 internship description

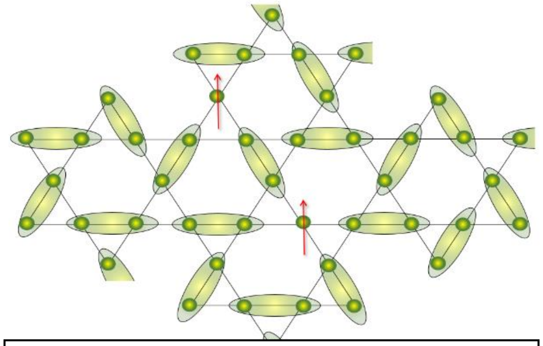


Fig. 1. Spinon excitation among a spin-singlet configuration on a kagome lattice.

Quantum spin liquids are fascinating new states of matter. Unlike conventional ferro- or antiferromagnetic ground states consisting of long-range ordered spins, spin liquids are highly entangled disordered states, which breaks the paradigm of the Landau-Ginzburg-Wilson theory of phase transitions. Quantum fluctuations are so strong that the semi-classical picture of individual spins, relevant for conventional states, completely collapses. Instead, the spins combine to form singlet states. Spin liquid states result from the quantum superposition of these individual singlets to form a macroscopically entangled state. A common footprint of these states is the emergence of unconventional excitations, fractional spinons, photon modes, majorana fermions... which can be detected experimentally (Fig. 1). Several materials are now synthesized and studied around the world and in our group for their unique magnetic properties. Rare earth pyrochlores, kagome and Kitaev magnets or quantum materials with strong spin-orbit coupling that exhibit frustrated lattices are promising avenues for achieving such exotic states (Fig. 2).

The hired PhD/M2 student will study such new spin liquid materials thanks to our well-established international collaborations, with an original experimental approach combining very complementary high-resolution spectroscopic techniques (NMR, muon spin relaxation, inelastic neutron scattering) and bulk thermodynamic measurements (ultrasound, specific heat) at very low temperature; pursuing our recent achievements in the field [see Nature Commun. 8, 14810 (2017), Nat. Phys. 16, 469-474 (2020) and Phys. Rev. X 12, 021015 (2022)].

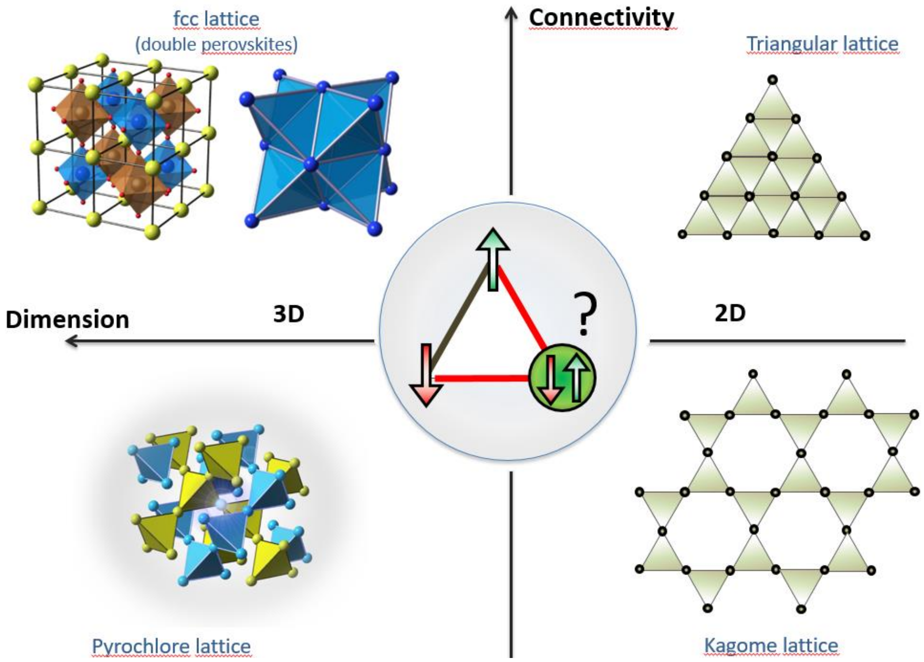


Fig. 2. Magnetic frustration is best illustrated on an antiferromagnetic triangle, where all interactions cannot be simultaneously satisfied (center). There is a variety of frustrated geometries that can be explored in real quantum materials.

Profile

We are seeking a highly motivated candidate, with a strong scientific background in condensed matter physics. He/she should have demonstrated excellent experimental skills, and will have the opportunity to learn state-of-the-art spectroscopic techniques (NMR, muSR, inelastic neutron scattering) along with bulk thermodynamic techniques (ultrasound, specific heat) under extreme conditions (low temperature, high magnetic field) in an international environment. The candidate should hold a Master degree. A good working knowledge of English is mandatory.

Starting date no later than December 2025. The hired PhD student will be based within the Spectroscopies of Quantum Materials team at the *Laboratoire de Physique des Solides* (Orsay, France) and have the opportunity to visit the *Department of Physics, University of Sherbrooke* (QC, Canada). The net salary is fixed by the CNRS and comes with benefits (health insurance, transportation,…).

Contact

For more information, please contact:

Dr. Edwin Kermarrec
edwin.kermarrec@universite-paris-saclay.fr, Phone: +33 (0) 169155340

Master 2: *International Centre for Fundamental Physics*
INTERNSHIP PROPOSAL

Laboratory name: ***Laboratoire de Physique des Solides***
CNRS identification code: UMR8502
Internship director'surnames: Julien BASSET and Jérôme ESTEVE
E-mail: Julien.basset@universite-paris-saclay.fr, Jerome.esteve@ universite-paris-saclay.fr
Phone numbers: 0033169158011, 0033169155365
Web page: https://equipes2.lps.u-psud.fr/ns2/

Internship location: Laboratoire de Physique des Solides -
Université Paris Saclay- Groupe NS2 – 1 rue Nicolas Appert 91405 Orsay

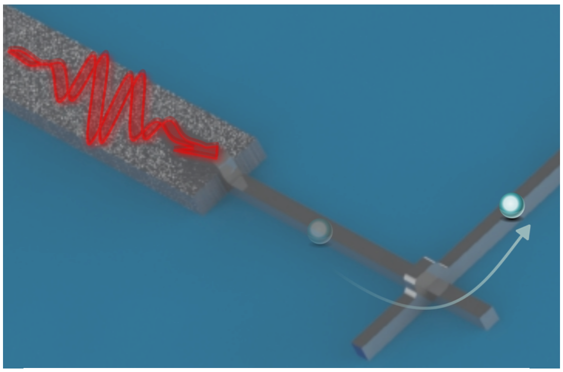
Thesis possibility after internship:	YES
Funding: YES/NO	If YES, which type of funding:

Towards photoelectric detection of single microwave photons using a super-inductance circuit

Subject :

With the advent of circuit quantum electro-dynamics, the most advanced platform to realize fully controllable and scalable quantum processors using superconducting quantum bits, the vector of information has become microwave photons in the [4-8]~GHz band. Developing an efficient and fast single microwave photon detector thus holds immense promise in advancing quantum computing, communication and sensing.

Historically, the technology used by optical photon detection is based on semiconductor materials whose gap appropriately matches the frequency domain of interest. Transferring this technology to microwave photons fails due to the natural mismatch between semiconducting gap and microwave frequency photons which carry about 10^5 times less energy than an optical visible one.



Artistic view of the ideal photoelectric effect demonstrated in reference [2].

We have recently overcome this problem by realizing a ***quasi-ideal microwave photon to electron converter*** in which a superconducting tunnel junction acts as a voltage tuneable quantum absorber through the photon-assisted tunneling of quasiparticles [1]. The achieved quantum efficiency, estimated from the measured photo-assisted current, approaches unity [2].

We are now seeking for an enthusiastic student to work on the development of ***detection techniques to measure the single charge associated to the absorption of a single microwave photon.*** In this project, the student will work closely with 2 permanent researchers and a freshly graduated phd student. The goal will be to develop charge detection using superconducting circuits made out of granular aluminum, a disordered superconductor, realized in a nanofabrication clean room by electron beam lithography and metal evaporation. Measurements will then be carried in a new dilution refrigerator with base temperature of 20mK and high precision electronics. The student will also get involved into numerical simulations of the quantum master equation governing the dynamics of the system.

[1] Aiello et al, *Quantum bath engineering of a high impedance microwave mode through quasiparticle tunnelling,* Nature Communications **13**, 7146 (2022). https://www.iledefrance-gif.cnrs.fr/fr/cnrsinfo/de-leffet-photoelectrique-aux-technologies-quantiques

[2] Stanisavljevic et al, *Efficient Microwave Photon-to-Electron Conversion in a High-Impedance Quantum Circuit*, Physical Review Letters **133**, 076302 (2024). https://physics.aps.org/articles/v17/127

Condensed Matter Physics:	YES	Macroscopic Physics and complexity:	NO
Quantum Physics:	YES	Theoretical Physics:	NO

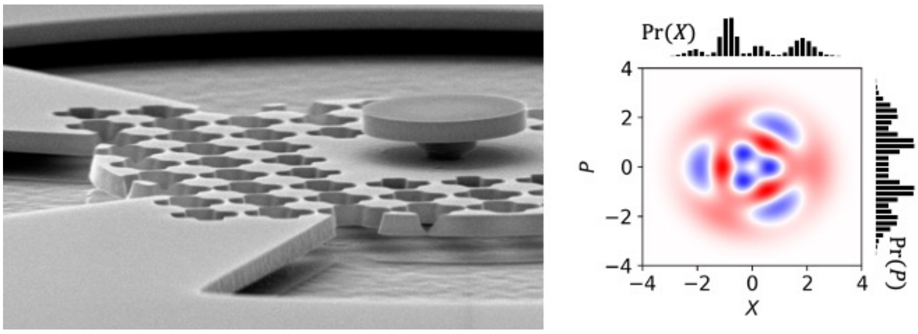
Internship/PhD offer
2024/2025

Laboratory: Matériaux et Phénomènes Quantiques
Director: Cristiano Ciuti
Address: Bâtiment Condorcet, 10 rue A. Domon et L. Duquet, 75013 Paris
Person in charge of the internship: Adrien Borne
Tel: 01 57 27 70 12
e-mail: adrien.borne@u-paris.fr

Quantum states of motion of a mechanical resonator

Scientific project:

Similarly to single atoms, the motion of massive, mesoscopic-scale mechanical resonators can behave quantum mechanically when cooled down to ultra-low temperatures. The study of quantum states of motion of such systems has both fundamental and practical interests: for testing quantum mechanics in systems beyond the few-particle ensembles, its interplay with gravitation; also in force sensing, or as a light-matter interface for the development of quantum communication networks, in particular for storing and transducing the quantum information.



Left: Scanning electron microscope image of an optomechanical disk resonator mechanically shielded from the environment (nanofabrication by our team). Right: Theoretical Wigner function of a superposition state.

In this context, this internship/PhD project aims at generating targeted quantum states of the motion of an optomechanical resonator such as the microdisk pictured above and developed in our group [1]. Fock and coherent superposition states will be considered, chosen arbitrarily in the low phonon number regime. This mechanical quantum information can be encoded in the device through its interaction with light [2,3], and then characterized through optical tomographic reconstruction [4]. This work will also consider increasing the dimensionality by including several optomechanical resonators, thereby involving entanglement of massive objects.

[1] M.R. Vanner, M. Aspelmeyer and M.S. Kim, PRL **110**, 010504 (2013).
[2] I. Favero and K. Karrai, Nat. Phot. **3**, 201 (2009).
[3] M. Aspelmeyer, T. Kippenberg and F. Marquardt, Rev. Mod. Phys. **86**, 1391 (2014).
[4] M.R. Vanner, I. Pikovski, and M.S. Kim, Ann. Phys. **527** (2015).

Methods and techniques: Quantum optics, nanomechanics, single-photon counting, quantum state tomography, cryogenics

Possibility to go on with a PhD ? Yes
Envisaged fellowship ? Yes, ANR project CREATION

Internship/PhD offer
2024/2025

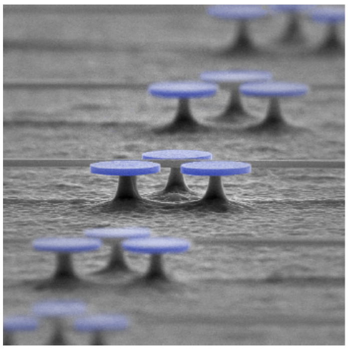
Laboratory: Matériaux et Phénomènes Quantiques
Director: Cristiano Ciuti
Address: Bâtiment Condorcet, 10 rue A. Domon et L. Duquet, 75013 Paris
Person in charge of the internship: Ivan Favero
Tel: 01 57 27 62 28
e-mail: ivan.favero@u-paris.fr

Optomechanical nanoscale quantum sensing

Scientific project:

Optomechanics, the interaction between light and mechanical oscillators, is a burgeoning field of research at the interface of quantum optics, mesoscopic physics and mechanical micro/nano systems [1].

Using light, it has recently been possible to control and read-out the quantum states of mesoscopic mechanical resonators. This has been notably achieved with nano-optomechanical disk resonators (see image below) fabricated in our team, where the simultaneous confinement of light and mechanical motion in a sub-micron volume enables strong optomechanical interaction [2]. The implications of such developments in the field of quantum sensing remain now to be explored.



This PhD project aims to bring mechanical scanning probes into the experimental quantum domain using optomechanics [3,4]. Quantum theory postulates indeed that energy exchanges between physical systems take place with a certain granularity, in quantities that are multiples of an energy quantum. This quantum regime of interactions has never been illustrated by local mechanical measurements, such as those made with an atomic force microscope (AFM). Detecting the exchange of a single quantum of energy between a physical system and mechanical force probe represents the ultimate level of sensitivity allowed by microscopic laws, and is therefore a considerable scientific and technological stake for sensing applications of optomechanics [5]. This PhD project aims at reaching this experimental regime, before addressing the subject of arbitrary quantum state production, for optimal sensing.

[1] I. Favero and K. Karrai. Nat. Phot. 3, 201 (2009). M. Aspelmeyer, Rev. Mod. Phys. 86, 1391 (2014).
[2] C. Baker, …, and I. Favero. Opt. Express 22, 14072 (2014).
[3] P. Allain et al., Nanoscale 12, 2939 (2020).
[4] L. Schwab et al, Microsystems & Nanoengineering 8 (1) 1 (2022).
[5] S. Sbarra, L. Waquier, S. Suffit, A. Lemaître and I Favero. Nature Communications 13 (1), 6462 (2022).

Methods and techniques: Quantum optics, nanomechanics, force sensing, low temperatures

Possibility to go on with a PhD ? Yes
Envisaged fellowship ? Yes, ANR project SINPHONY

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INTERNSHIP OFFER

Reference: **DPHY-2025-000**
Location: Palaiseau
Laboratory: DPHY / SLM
Tel.:
Supervisors: Jean-Michel Melkonian, Julien Le Gouët
Email.: Jean-Michel.Melkonian@onera.fr
Julien.Le_Gouet@onera.fr

DESCRIPTION

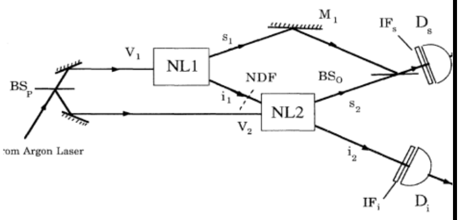
Themes: Laser, nonlinear optics, metrology, quantum optics

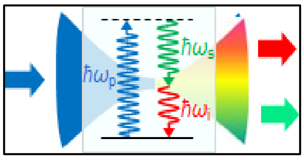
Graduation: ☒ Master 2 ☐ Master 1 ☐ Licence ☐ Baccalaureate

Title: Quantum interferometer for gas detection

Famous experiments involving optical interferometers for the detection of gravitational waves, or atomic sensors (clocks, gravimeters), show that the use of certain quantum states can significantly improve the sensitivity of fundamental metrology experiments. On the other hand, for remote measurements in difficult environments (with losses, background noise, etc.), quantum optics, often relevant at low photon number, have yet to demonstrate a decisive advantage over classical optics, in which photon fluxes can be made much higher when needed.

In this context, we propose to study an interferometer including two optical frequency conversion crystals (i.e. twin photon generators), and compare the key parameters under the quantum and classical regimes. The main asset of this non-linear interferometer is to be able to probe an object in the infrared (like a gas showing strong absorption lines), while detecting all the photons in the visible spectrum, where photodetectors are very sensitive.





The internship will consist in using the current interferometer, which emits at 1.5+4µm when pumped at 1.064 µm by sub-nanosecond laser pulses. The internship will provide an opportunity to perfect laser techniques, non-linear optics (frequency conversion) and quantum optics (correlation measurements, coincidences, etc.).

The internship may lead to a thesis, consisting in pumping the interferometer at a shorter wavelength and performing wavelength resolved measurements on gases, as well as comparisons with setups owned by academic partners (MPQ lab and LUMIN).

Note: ONERA is a Zone à Régime Restrictif (ZRR), requiring administrative inquiry and access clearance from the Ministry of Defense, a procedure which can take up to 2 months.

Pair work? No

Type of work:

☒ Theory ☒ Experiments

☒ Numerical simulation ☒ Bibliography

Thesis opportunity: Yes

Duration: At least: 3 months Up to: 5 months

When: Spring 2025

CANDIDATE PROFILE

Knowledge and know-how: Laser, optics, basics of quantum physics	Soft skills: Deft fingers, organized, like to report

Internship proposal: Causal decompositions of unitary processes

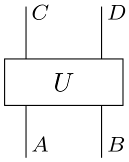
Supervisor: Augustin Vanrietvelde
Quriosity team, Télécom Paris
vanrietvelde@telecom-paris.fr

Background

In recent years, the field of quantum foundations has seen a surge in interest for the subject of *quantum causal modelling*: pinning down how the notion of causal influence could be conceptually understood and mathematically formalised in quantum theory, given the failure of classical notions of causality, as exemplified by the violation of Bell inequalities [1, 2, 3]. The hope is to better understand quantum theory's core structure, and therefore what it tells us about the world.

In that context, a particularly important conjecture has emerged, that of the existence of *causal decompositions* [4]. It concerns the relationship between two core structures of quantum theory:

1. *Causal structure*, on the one hand, is about empirically detectable influences from one quantum system to another in a unitary evolution. For instance, given a unitary $U : \mathcal{H}_A \otimes \mathcal{H}_B \to \mathcal{H}_C \otimes \mathcal{H}_D$ from two systems A and B to two systems C and D, a possible causal structure for U would be that it features no causal influence from A to D, i.e. that operations performed on A before U takes place do not affect the outcome probabilities in measurements performed on D after U takes place. We can denote this as:

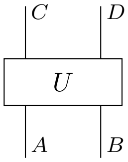


$$: \quad A \not\to D \,. \tag{1}$$

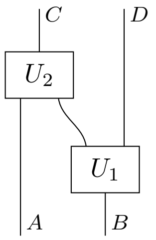
   Note how causal structure involves *operational quantities*, i.e. the statistics that can be collected in concrete experiments. It is about what can be probed in a lab with access to U.

2. *Compositional structure*, on the other hand, is about the possibility for a certain unitary map to be seen as the mathematical composition of 'smaller' unitary maps. For instance, a possible compositional structure for the previous gate U would be the existence of the following decomposition:

$$\exists U_1, U_2,$$



$$=$$



$$. \tag{2}$$

   Compositional structure is about *underlying mathematical structure*: it concerns handy ways in which we can write down the mathematical objects describing the dynamics of the world. It might also tell us about 'what is going on deep down', i.e. about the fine-grained dynamics underlying a given coarse-grained one. The downside of this is that compositional structure has no direct operational meaning, i.e. does not directly relate to what can be probed in a lab with access to U.

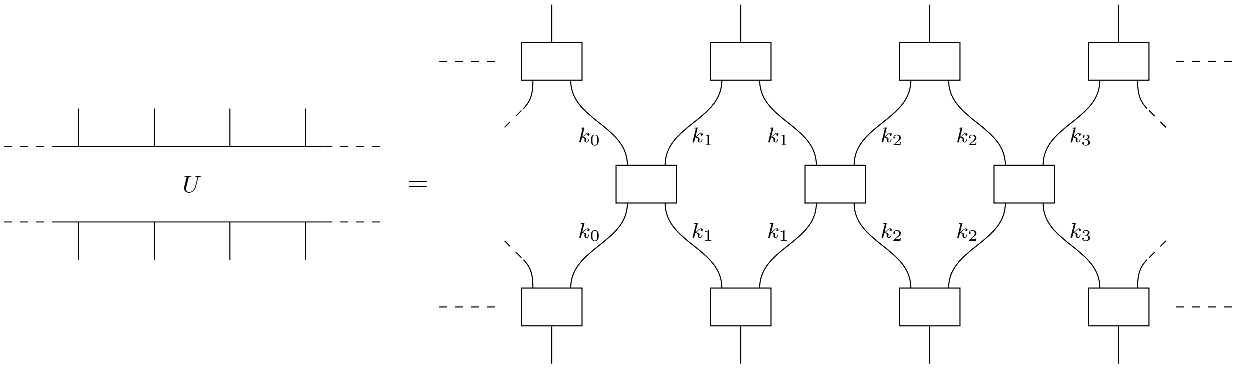


Figure 1: Causal decomposition of a 1D QCA with radius 1. A 1D QCA (as represented on the left) is a unitary on a 1D array of sites $\ldots, A_{-1}, A_0, A_1, \ldots$ such that a given input site only affects the output sites less than a certain causality radius away from it (for instance, in radius 1, A_0 only affects A_{-1}, A_0 and A_1, etc). The causal decomposition for a QCA with causality radius 1 is represented on the right (higher radii simply correspond to more layers). The k-superscripts correspond to the language of routed circuits.

(2) implies (1), since it directly shows that there is 'no path' from A to D. But remarkably, the reverse implication is also true, so (1) and (2) are equivalent statements [5]. The conjecture of causal decompositions is that this equivalence holds in general: for a unitary with arbitrarily many inputs and outputs, any given causal structure (i.e. a set of no-influence relations between the inputs and outputs) is equivalent to a corresponding compositional structure [4]. Proving this conjecture in general would be of great importance: it would unveil a remarkable correspondence between the operational and the mathematical structures of quantum theory, between 'what we can empirically probe' and 'what is going on deep down in the Universe'.

Investigating this conjecture has yielded important structural results about quantum theory already; for instance, it has shown the need to go beyond the formalism of unitary circuits to a more flexible one, that of unitary *routed* circuits. Recently, a major step forward has been attained with the proof that causal decompositions exist for *1D quantum cellular automata* (1D QCAs) – see Figure 1. This essentially shows that causally acceptable dynamics in a (discretised) 1+1D spacetime are all and only those consisted of a series of nearest-neighbours interactions. The proof techniques for this result involve the use of the theory of C*-algebras, with several new methods, and are of interest in themselves.[1]

The project

The previous result about causal decompositions of 1D QCAs has a caveat: it applies only to 1D QCAs over a finite array of sites – in other words, the series $\ldots, A_{-1}, A_0, A_1, \ldots$ cannot be infinite (it either stops at two ends, or is looped around). This limitation is due to the fact that the proof techniques have so far only been developed for *finite-dimensional* C* algebras, while an infinite array of sites would necessarily involve the consideration of infinite-dimensional ones. The shift to infinite dimension involves numerous mathematical complications, due to the appearance of convergence considerations.

The project would thus be for the student to investigate a generalisation of that result to infinite dimension. It would involve carefully analysing the finite-dimensional definitions and proofs and adapting them to the infinite-dimensional case. Although this will be quite technical, it is a somewhat safe project, in the sense that there is no reason to fear that the result wouldn't hold in infinite dimension. On the other hand, the outcome would still be of great significance and interest. Pinning down the generalisation of these new C*-algebraic techniques to infinite dimension would also be very likely to lead to application to other domains besides that particular outcome.

---

[1] The two papers describing the methods and the result will be on the arxiv soon; in the meantime, drafts are available upon request.

Profile of the student

The student should have followed a relevant curriculum in theoretical physics, mathematics, or computer science. This project requires a student with a solid mathematical background, and a willingness to dive into complicated maths. The physics is still there, and the project's outcome would hold direct physical significance, but the path might be somewhat dry. It is not imperative to have followed a course on operator algebras before, but that would of course be welcome.

The internhip could continue into a PhD.

Location

The internship will take place at Télécom Paris in the Quriosity team, supervised by Augustin Vanrietvelde. Quriosity brings together physicists and computer scientists to explore the fundamental informational aspects of quantum theory.

References

[1] R. W. Spekkens, "The paradigm of kinematics and dynamics must yield to causal structure," `arXiv:1209.0023 [quant-ph]`.

[2] J.-M. A. Allen, J. Barrett, D. C. Horsman, C. M. Lee, and R. W. Spekkens, "Quantum common causes and quantum causal models," *Physical Review X* **7** (2017) 031021, `arXiv:1609.09487 [quant-ph]`.

[3] J. Barrett, R. Lorenz, and O. Oreshkov, "Quantum causal models," `arXiv:1906.10726 [quant-ph]`.

[4] R. Lorenz and J. Barrett, "Causal and compositional structure of unitary transformations," *Quantum* **5** (2021) 511, `arXiv:2001.07774 [quant-ph]`.

[5] T. Eggeling, D. Schlingemann, and R. F. Werner, "Semicausal operations are semilocalizable," *Europhysics Letters (EPL)* **57** no. 6, (2002) 782–788, `arXiv:quant-ph/0104027`.