# 2024 Giambiagi Winter School "Mechanical Systems at the Quantum Level"

Monday, 22 July 2024 - Saturday, 27 July 2024

# Book of Abstracts

# Contents

# School courses

**1**

## Single electrons, single spins, and mechanical resonators

**Speaker:** Natalia Ares

**Affiliation:** University of Oxford

At the nanoscale, single electrons and single spins can be isolated. Also, mechanical resonators with large quality factors can be built. More interestingly, a rich interplay between mechanics, electron tunnelling and spin states can be engineered. I will talk about state-of-the-art platforms, the experiments that they have enabled for us and others and show the promising avenues they pave for future research.I will present how we measured the thermodynamic cost of timekeeping using a membrane just a few tens of nanometers thick. We find that the accuracy of our clock and the entropy produced by it are proportional, as predicted both for classical and quantum regimes. I will also introduce the exceptional properties of fully suspended carbon nanotube devices, combining electron tunnelling, spin physics, and motion. In these devices, we find that the coupling of electron transport to the nanotube displacement is ultra-strong. This coupling opens a wide range of possibilities for the development of promising applications in quantum information processing, high-precision sensors, cooling, and in the exploration of the foundation of quantum mechanics. We also find that the interplay between single electron tunnelling and mechanical motion, in the absence of a mechanical drive, can give rise to self-sustained oscillations. Fluctuations can make these self-oscillations irrupt, vanish, and exhibit a bistable behaviour causing hysteresis cycles. We find that self-oscillations can be stable for over 20 seconds, many orders of magnitude above electronic and mechanical characteristic timescales. I will show that the combination of single electron tunnelling and Duffing effects give rise to interesting non-linear dynamics in nanomechanical resonators. Non-linearities are particularly relevant for the exploration of chaos and for the development of spiking neurons.

**BIO:** Natalia Ares is currently an associate professor at the University of Oxford. She works on experiments to advance the development of quantum technologies, focusing on the use of artificial intelligence for controlling quantum devices and quantum thermodynamics. She has received several research grants, including the Marie Skłodowska-Curie and a Royal Society University Research Fellowship. Additionally, in 2020, she received a grant from the European Research Council. During her doctoral studies, she researched silicon and germanium-based devices for quantum computing at CEA Grenoble, France. She graduated with a Bachelor of Science in Physics from the University of Buenos Aires in CABA, the city where she was born and raised. Since October 2021, she has been an Associate Professor and Tutorial Fellow at New College, University of Oxford.

**2**

## Quantum sensing

**Speaker:** Diego Dalvit

**Affiliation:** Los Alamos National Laboratory

Quantum sensing promised to revolutionize sensing technologies by employing quantum states of light or matter as sensing probes. This lecture series will describe the basic theory of quantum sensing, imaging, and metrology. In the first lecture we will discuss the theoretical underpinnings of quantum sensing bases on a phase space approach and Cramer-Rao bounds. The second lecture will be devoted to describing recent experimentsÊ using light and atoms as sensing probes. Finally, the last lecture will cover a recent discovery by the speaker of quantum remote sensing based on quantum frequency combs and quantum-induced coherence by path identity . The topics covered in these lectures will give a glimpse of the profound implications quantum sensing has for fundamental and applied science.

**BIO:** Diego Dalvit is a staff scientist at the Theoretical Division of Los Alamos National Laboratory. He earned a PhD in Physics from University of Buenos Aires (1998), was a Director's Postdoctoral Fellow at LANL (1999-2001), and became a permanent staff at LANL in 2002. He is an APS Fellow for his work on Casimir physics, and APS Outstanding Referee. His research interests are in quantum optics, quantum sensing, Casimir physics, and metamaterials. He published 2 books, 2 patents, 3 review papers, and >110 research papers, with total citations > 8400 and h-index of 47. He leads the quantum optics theory team at Los Alamos, that involves staff, postdocs and students working on various topics, ranging from space-time quantum metasurfaces to remote quantum sensing.

**3**

## Mechanical systems at the quantum limit to detect weak interactions

**Speaker:** Ricardo Decca

**Affiliation:** Nanoscale Imaging Center, Indiana University

The success of the Standard Model (SM) in describing matter and interactions cannot be overstated, however it does not provide a complete description: it does not explain dark matter and dark energy, it predicts CP violations in the strong force which have not yet been observed, and there is no quantized description of gravity. This incompleteness has led to many theories to fill the gaps of the SM. One such approach is hypothesizing an interaction mediated by an as of yet undiscovered boson. If the hypothetical boson is massive it leads to Yukawa-like interactions, but if it is massless the interaction will be parameterized with a power law. It is surprising that in some range of parameters the strength of these hypothetical interactions is up to 20 orders of magnitude and it still has not been experimentally detected (or ruled out). One of the main problems to access the relevant strength is that the interacting bodies need to be placed in close proximity, at submicron separations, where vacuum fluctuations are dominant. Even when the effects of vacuum fluctuations are taken into account, the interaction is so small, that the detection system has to be exquisitely sensitive.

In my lectures I will present the different techniques and approaches used to first construct mechanical transducers able to shed light on potential interactions, and then how working in the quantum regime, where $k_B T << \hbar\Omega$ (where $\Omega$ is the characteristic frequency of the mechanical oscillator), allows for a better detection. Characteristic fundamental and technical limiting factors will be described, and current and future methods to mitigate the interaction of the mechanical system with the environment will be presented and discussed.

**BIO:** Ricardo Decca (Department of Physics, Indiana University Indianapolis, USA) Ricardo Decca, Professor and Chair in the Department of Physics at Indiana University Indianapolis, got his "Licenciatura"(a989) and PhD (1994) degrees from Instituto Balseiro, Argentina. He was a postdoc at the University of Maryland, USA, and in 2000 he became an Assistant Professor at Indiana University Indianapolis (then Indian University-Purdue University Indianapolis). He is co-director of the Nanoscale Imaging Center, and a founding member of the Indiana University Center for Space Symmetries (IUCSS) and the Indiana University Quantum Science and Engineering Center (QSEc), and the campus director for the Center for Quantum Technologies (CQT), a consortium between Purdue University, Indiana University and the University of Notre Dame. As a member of the American Physical Society, he he was elected a fellow in 2015 for his pioneering precision experiments in the fields of Casimir physics and new fundamental interactions. His work revolves around finding new approaches to measure feeble interactions between bodies. He uses a battery of approaches to achieve that goal, centered around scanning probes, and development of new experimental techniques.

**4**

# Cavity optomechanics with polariton fluids

**Speaker:** Alex Fainstein

**Affiliation:** Photonic and Optoelectronic Laboratory, Balseiro Atomic Center (CAB)

Cavity resonators are essential to adapt and improve interactions between photons, two-level systems, and vibrations. In this context, two important areas represent, on the one hand, systems with strong light-matter coupling, which leads to cavity exciton polaritons, and on the other hand, cavity optomechanics, which has allowed the demonstration of dynamical backaction phenomena in the interaction between light and vibrations. In the field of polaritonics, Bose-Einstein condensates of these strongly interacting quasi-particles ("light fluids") have been demonstrated. In cavity optomechanics some milestones represent laser cooling to the quantum limit, and the stimulated emission of hypersound. Traditionally, these two areas have had little overlap, although their cross-fertilization represents a challenge that promises paradigmatic shifts in the control and applications of light-matter interactions. In these introductory talks I will describe what these fields are and how, on the one hand, polaritons enhance interactions between photons and phonons and, on the other hand, phonons confined in these resonators introduce novel and controllable dynamics in polaritonic Bose-Einstein condensates. Phenomena such as piezoelectric control of optical resonances at GHz frequencies, stimulated phonon emission, asynchronous locking of optical resonances, access to strong photon-exciton-phonon coupling phenomena as a path for microwave-light frequency conversion, spatio-temporal modulation to induce non-reciprocal transport, and the demonstration of continuous time crystals, are some of the consequences of combining photons, excitons, and phonons in semiconductor resonators.

**BIO:** He is a member of the Photonics Optoelectronics Group formed at the CAB, a researcher at CNEA (National Atomic Energy Commission), Full Professor at the Balseiro Institute, and Senior Researcher at CONICET (National Scientific and Technical Research Council). He is internationally recognized for research related to light and sound confinement in nano and micro semiconductor structures, as well as ultra-sensitive optical detection of molecules. He has supervised 10 doctoral theses and over a dozen master's theses. He has published more than 180 papers in international journals and has given approximately 60 Invited Lectures at International Forums. He was a fellow of the Alexander von Humboldt Foundation and the Max Planck Society of Germany, and an Associate Researcher at CNRS (National Center for Scientific Research) in France. He is a member of the National Academy of Exact, Physical, and Natural Sciences. He has been honored as a Fellow of the Guggenheim Foundation (2001); received the Bernardo Houssay Prize from SECyT (Science and Technology Secretary) and the Merit Award from the Municipal Council of San Carlos de Bariloche (2003); received the Scientific Quality Award Dra. Elizabeth Jares-Erijman from FAN (Argentine Foundation for Nature) in 2012, and the Konex Award in 2013.

**5**

# Time Crystals and synchronization in quantum systems

**Speaker:** Rosario Fazio

**Affiliation:** The Abdus Salam International Centre for Theoretical Physics, Trieste

**Main topics of the talks:**

–Introduction to quantum many-body open systems

–Time crystals in closed and open systems

–Applications in quantum sensing and quantum thermodynamics

**BIO:** Rosario Fazio received his PhD in Physics in 1990 at the University of Catania. He held the chair of theoretical condesed matter at SISSA –Trieste (2005 –2008) and at Scuola Normale Superiore di Pisa (2008 –2019). He is currently Head of the Condensed Matter and Statistical Physics Section of the Abdus Salam International Center for Theoretical Physics (Trieste) and Professor of Theoretical Condensed Matter Physics at the University of Naples "Federico II". He is the Director of the Institute for Quantum Theoretical Technologies of Trieste. His reseach interests are in theoretical condensed matter and quantum information processing focusing on quantum transport in nano-devices, mesoscopic superconductivity, quantum simulators, quantum information many-body systems, open many-body systems.

**6**

## Levitated mechanical systems for experiments at the quantum level

**Speaker:** Tracy Northup

**Affiliation:** Quantum Interfaces Group, Institute of Experimental Physics, University of Innsbruck

Mechanical systems can be levitated —that is, suspended against gravity —using electric, magnetic, or optical forces. In recent decades, levitated atoms and molecules have been prepared in highly nonclassical states, which has led both to new insights into quantum mechanics and to novel quantum technologies. It is now hoped that levitation of much larger objects, consisting of billions of atoms, will enable similar breakthroughs. In these lectures, we will survey the mesoscopic mechanical systems with which researchers aim to reach the quantum regime. We will examine the current state of the art; the advantages and limitations of different trapping methods; and the experimental challenges inherent to preparing, manipulating, and measuring quantum-mechanical states of motion. The specific case of nanoparticles suspended in a linear Paul trap (ion trap) will be considered in detail.

**BIO:** Tracy Northup is a professor of experimental physics at the University of Innsbruck, Austria. Her research explores quantum interfaces between light and matter, focusing on trapped-ion and cavity-based interfaces for quantum networks and quantum optomechanics. She received her PhD from the California Institute of Technology in 2008 and then held an appointment as a postdoctoral scholar at the University of Innsbruck, where she was the recipient of a Marie Curie International Incoming Fellowship and an Elise Richter Fellowship. She became an assistant professor at the University of Innsbruck in 2015 and has been a full professor since 2017; she held an Ingeborg Hochmair Professorship from 2017 to 2022. In 2016, she received the START Prize, the highest Austrian award for young scientists, from the Austrian Science Fund. In 2023, she received Optica's Gordon Memorial Speakership.

**7**

## Quantum mechanics and decoherence in Wigner space: theoretical modeling of proposed experiments

**Speaker:** Oriol Romero-Isart

**Affiliation:** Institute of Photonic Sciences, Barcelona

The ability to manipulate, measure, and control levitated nanoparticles and microparticles in an ultra-high vacuum environment has opened new horizons for both fundamental and applied research [1]. In this series of conferences, we will develop a theoretical framework to describe and understand the dynamics of the center of mass motion of such levitated particles. Our goal is to design and optimize an experimental proposal that unequivocally demonstrates their quantum mechanical nature. First, we will introduce the Wigner-Weyl formalism of quantum mechanics, which provides a clear distinction between the classical, quantum, and open dynamics of a quantum mechanical system. Equipped with this formalism, we will shift our focus towards the experimentally relevant and theoretically challenging realm of broad potentials and small fluctuations. Specifically, we will discuss a new numerical tool [2] capable of providing a numerically exact simulation of the quantum dynamics of the Wigner function in this challenging regime. We will complement this numerical tool with an analytical approach to dynamics [3], helping us understand the scaling and dependencies of various system parameters. Finally, we will use the tools we have developed to explore an experimental proposal [4] aimed at preparing the center of mass of a levitated particle in a macroscopic quantum superposition state, a state without a classical analogue. If successfully demonstrated in experiments, this macroscopic superposition state could pave the way for studying the gravitational field of a source mass placed in "two places at the same time," which could shed light on the quantum or classical nature of gravity.

**BIO:** Oriol Romero-Isart is, since May 2024, an ICREA professor and group leader at ICFO (Barcelona) and future director of the Institute starting from September 2024. Romero-Isart obtained his doctorate from the Universitat Autònoma de Barcelona in 2008. After a postdoctoral stint at the Max-Planck Institute for Quantum Optics in

Munich with Ignacio Cirac, he moved to Innsbruck to start his own research group in 2013. There, he was a professor at the University of Innsbruck, group leader at the Institute for Quantum Optics and Quantum Information (IQOQI) Innsbruck, and deputy director of IQOQI. His research group focuses on topics in the fields of theoretical quantum optics and mesoscopic quantum physics in the context of quantum science and technology.

**8**

## Casimir nanoparticle levitation  stochastic oscillators

**Speaker:** Gustavo Widerhecker

**Affiliation:** Device Research Laboratory, Universidade Estadual de Campinas

The strength of Brillouin scattering critically depends on the momentum conservation and spatial overlap between optical and mechanical fields. Within wavelength-scale waveguides and cavities, optical and mechanical fields are fully vectorial and the common intuition that more intense fields lead to stronger interaction may fail. In this tutorial, the major aspects ofoptical and mechanical wave confinement will be explored. We will provide a thorough discussion on how the two major physical effects responsible for the Brillouin interaction –photoelastic and moving-boundary effects– interplay to foster exciting possibilities in this field. Case studies of this interaction will be discussed and shared with the audience based on finite-element analysis through a commercial multiphysics solver.

**BIO:** Gustavo Wiederhecker holds an Associate Professor position at the University of Campinas, his research laboratory targets at harnessing nonlinear optical phenomena within microphotonic devices, with emphasis in the interaction between light and mechanical waves. Before joining University of Campinas in 2011, he earned his B.Sc. and Ph.D. degrees in Physics from the same University and has been a postdoctoral fellow at Cornell University from 2008-2011. He is an affiliate member of the Brazilian Academy of Sciences and Associate Editor of the Journal of The Optical Society of America B (JOSA B) since 2020.

# Invited talks

**1**

## Casimir nanoparticle levitation  stochastic oscillators

**Speaker:** Adrian Rubio Lopez

**Affiliation:** Millenium Institute for Research in Optics (MIRO)

In this talk I will first start introducing the basics of Casimir forces. Then, I will present a recent proposal to implement these forces for nanoparticle levitation. The levitation of nanoparticles is essential in various branches of research. Casimir forces are natural candidates to tackle it but the lack of broadband metamaterials precluded repulsive forces in vacuum. We show sub-micron nanoparticle levitation in vacuum only based on the design of a broadband metamaterial perfect magnetic conductor surface, where the Casimir force is mostly given by the (quantum) zero-point contribution and compensates the nanoparticle's weight. In the harmonic regime, the volume-independent characteristic frequency depends linearly on Planck's constant. In the second part, I will introduce some basics of the dynamics of oscillators with stochastic parameters, which might apply to different current experimental scenarios. Specifically, I will introduce stochastic-frequency Brownian oscillators, showing that control on energetic aspects can be achieved. The latter can be exploited, for instance, in heat transport as a novel method of control.

**2**

## Nanomechanics with nanoantennas

**Speaker:** Andrea Bragas

**Affiliation:** Quantum Electronics Laboratory, University of Buenos Aires (UBA)

The optical pulsed excitation on plasmonic nanoantennas and subsequent hot electron decay into coherent acoustic phonons produce a periodic modulation of their optical properties. In addition, these minimal and fast modulations can be detected optically with remarkable sensitivity, allowing their exploitation as exquisitely sensitive mechanical probes of their local environment. During this presentation, I will present recent advancements in utilizing these nanoantennas as efficient energy transducers at the nanoscale within phononic-plasmonic platforms, studied at the individual level. We will also discuss the all-optical generation of hypersonic acoustic waves with nanoantennas and the importance of their manipulation for potential nanomechanical devices operating in the GHz range and the nanoscale.

**BIO:** Andrea Bragas is an Associate Professor at the Department of Physics, School of Sciences at the University of Buenos Aires (UBA) in the field of Nanophysics and Nanotechnology. She did her PhD at UBA in the field of near-field optics, pioneering studies in laser-assisted microscopies and near-field enhancement in plasmonics. She later moved to Ann Arbor to do his postdoc at the University of Michigan, working on solid-state physics and ultrafast optics, where, among other developments, they achieved the experimental demonstration of the entanglement of three electrons in a crystalline material (three qubits) after the passage of a light pulse. Her group in Buenos Aires carries out a wide variety of fundamental and applied research ranging from unraveling the interaction of light with matter at the nanoscale to developing ultrasensitive sensors, efficient sources of optical harmonic generation, plasmonic photocatalysts for water remediation, and mechanical nano-resonators. Among other distinctions, she's got the 2023 Georg Forster Research Award from the Alexander von Humboldt Foundation.

# Coloquios

**1**

## Inteligencia artificial para construir computadoras cuánticas

**Speaker:** Natalia Ares

**Affiliation:** University of Oxford

Machine learning, la tecnología detrás de hazañas como ChatGPT, la victoria de AlphaGo sobre un campeón mundial de Go y la capacidad de reconocer rostros con precisión superior a la humana, ahora está causando una verdadera revolución en la ciencia de materiales y dispositivos cuánticos.

En esta charla voy a explicar cómo estamos utilizando machine learning para estudiar chips semiconductores a escalas nanométricas; dispositivos con los que esperamos fabricar una nueva generación de computadoras, que llamamos cuánticas.

Al igual que un jugador de Go o ajedrez que consigue balancear estrategias de corto y largo plazo, nuestros algoritmos pueden tomar decisiones inteligentes. Estas decisiones le permiten extraer la mayor cantidad de información sobre los dispositivos y usarla para encontrar rápidamente los efectos cuánticos que buscamos. Voy a mostrar cómo estos avances están abriendo puertas en el mundo de la ciencia, haciendo que tareas complejas sean más fáciles y precisas que nunca.

**1**

## Cristales (temporales)

**Speaker:** Alex Fainstein

**Affiliation:** Photonic and Optoelectronic Laboratory, Balseiro Atomic Center (CAB)

Se llaman cristales temporales a sistemas de muchas partículas en los que se rompe de manera espontánea la simetría de traslación temporal, en analogía con la ruptura de simetría espacial cuando los átomos se ordenan periódicamente formando un cristal. Su existencia fue propuesta teóricamente hace más de diez años, y luego negada, generando un intenso debate y motivando diversos caminos para su verificación experimental. En esta charla hablaré sobre nuestra reciente observación de cristales temporales “continuos”. Excitando un material con un láser cuya intensidad es constante en el tiempo, observamos millones de electrones y fotones oscilando colectivamente de forma periódica y persistente, sumando además millones de cuantos de sonido que terminan controlando el ritmo de todas las oscilaciones. En el camino, hablaré sobre el orden cristalino y sus implicancias, el concepto de cuasi-partículas en materia condensada, los sistemas fuera del equilibrio, la sincronización y las bifurcaciones. Y, además, sobre las ambigüedades y certezas en ciencia.

# Posters

**1**

## Master Equations for Generalized Subsystems

**Author:** Mariana Teixeira Santos[1]

**Co-authors:** Raul Vallejos [1]; Fernando de Melo [1]

[1] *Centro Brasileiro de Pesquisas Físicas (CBPF)*

**Corresponding Authors:** vallejosrauloscar@gmail.com, fmelo.cbpf@pm.me, maritexera.s@gmail.com

With the control of increasingly complex quantum systems, the relevant degrees of freedom we are interested in may not be those traditionally addressed by statistical quantum mechanics. Given a strong interaction among the systems' components, a split between system and environment may become ill defined, and traditional methods are no longer able to track the dynamics of the relevant degrees of freedom. In this project we employ the concept of generalized subsystems - subsystems generated by arbitrary quantum channels - in order to describe effective systems, for which we aim at deriving physically meaningful master equations.

**2**

## Quantum thermodynamics via NMR

**Author:** Lais Silva[1]

**Co-author:** Roberto Sarthour [1]

[1] *Centro Brasileiro de Pesquisas Físicas (CBPF)*

**Corresponding Authors:** laisajsjesus@gmail.com, robertocbpf@gmail.com

The project consists of using the technique of nuclear magnetic resonance (NMR) to study open quantum systems and thus explore concepts of quantum thermodynamics. Through NMR, we implement quantum circuits that describe protocols for measuring thermodynamic quantities, such as the quantum work of a qubit. By changing parameters of the system we can evaluate how these modifications interfere with the quantum work distribution.

**3**

## Automatic re-calibration of quantum devices by reinforcement learning

**Author:** Tomás Crosta[1]

**Co-authors:** Fernando Vilariño [2]; Lorena Rebón [3]; Matías Bilkis [1]; Mauricio Matera [3]

[1] *Computer Vision Center*

[2] *Universidad Autonoma de Barcelona*

[3] *Universidad Nacional de La Plata*

**Corresponding Author:** tomycrosta@gmail.com

Quantum hardware is highly sensitive to environmental changes, often resulting in the recurrent detuning from the optimal settings. This poses a challenge because detailed environmental modeling can be computationally prohibitive, and direct measurements of the state are both costly and noise-inducing. These issues restrict the applicability of quantum devices, which require a precise configuration in order to outperform classical technologies.

In this contribution, we propose a framework based on reinforcement learning techniques to develop a model-free control loop for the continuous recalibration of quantum devices. Additionally, we explore the advantages of incorporating information from simple environmental noise models, demonstrated through the numerical simulation of a Kennedy receiver for long-distance quantum communications. This approach paves the way for new calibration methods that could enhance the reliability and performance of quantum devices in practical applications. Preprint Arxiv 2404.10726

**4**

## Cold atom-atom-ion three-body recombination assisted by radiofrequency trap

**Author:** Ana Noguera[1]

**Co-authors:** Mateo Londoño [2]; Javier Madroñero [1]

[1] *Department of Physics, Universidad del Valle*

[2] *Department of Physics and Astronomy, Stony Brook University*

**Corresponding Authors:** mateo.londono@correounivalle.edu.co, javier.madronero@correounivalle.edu.co, ana.noguera@correounivalle.edu.co

We seek to develop a molecular dynamics simulation to study the recombination process of three cold bodies: atom-atom-ion, in the presence of a Paul trap. Previous work has demonstrated the existence of vibrational resonances in cold atom-ion collisions under the influence of a radiofrequency field. The lifetimes of these resonances reach nanoseconds, which would allow the interaction of the dimer with a third atom. As a result of this interaction, three-body recombination can occur, in which the third atom subtracts energy from the dimer, converting it into a stable diatomic molecule. To study this inelastic process, a molecular dynamics simulation is developed in which the equations of motion associated with the three bodies are completely solved, considering that the ion interacts first with one of the atoms, followed by the second interaction. Through these simulations, we seek to calculate the recombination rates of the three bodies and the possibility of modifying these values through the parameters associated with the radiofrequency trap and the atomic species involved.

**5**

## Exploring Quantum Light Sensitivity in the Human Eye: An Experimental Proposal

**Authors:** Alice Marques Aredes Rodrigues[1]; Bruss Lima[1]; Carlos Monken[2]; Filomeno Araujo[1]; Gabriel Horacio Aguilar[1]; Gabriela Barreto Lemos[1]; Gustavo Rohenkhol[3]; Jorge Moll[4]; Marcelo França[1]

[1] *Universidade Federal do Rio de Janeiro*

[2] *Universidade Federal de Minas Gerais*

[3] *Universidade de São Paulo*

[4] *IDOR*

**Corresponding Author:** alicemarques@pos.if.ufrj.br

The limits of human visual perception are not totally established in academic literature. Some experiments have shown that rod cells (the photoreceptor cells that are more sensitive to low light in comparison to cone cells) in vitro are sensitive to single photons and another experiment claims that humans can distinguish single photons. But can humans distinguish between a classical light source and a light source with quantum properties? To answer this question we propose an experimental setup that directs to the human eye light that switches randomly between a source of faint light composed of bunched photons and a source composed of superbunched photons. The photon bunching is a property of the incoherent light from conventional sources and superbunching is a phenomenon that can only be explained by a quantum theory. In that way a different response of the volunteers to one of those sources would indicate some sort of capability of distinguishment.

**6**

## Robustness and Generation of Entanglement in Spin Chains

**Authors:** Eduardo Kronbauer[1]; Fabiano Manoel de Andrade[1]; Paulo Rosas[1]

[1] *State University of Ponta Grossa*

**Corresponding Authors:** edukso2002@gmail.com, fmandrade@uepg.br

Entanglement is a very important phenomenon that has applications in various fields. For example, in the field of quantum cryptography, entangled states are used to create a key that makes it impossible for an unwanted observer to obtain information meant to be kept private. It is possible to generate a pair of entangled states through a protocol based on a chain of 7 spin-1/2 particles with strong and weak couplings. The protocol begins with the injection of two states at the ends of the chain, and then the system naturally evolves until the mirror time, at which point the states at the ends of the chain become maximally entangled. At this point in time, the states at the ends of the chain can be extracted from the positions at the ends of the chain, if desired.

**7**

## Investigating Apparent Violations of the Second Law of Thermodynamics in a Quantum-Classical Interaction

**Author:** Pedro Paraguassú[1]

**Co-authors:** Luca Abrahão [1]; Thiago Guerreiro [1]

[1] *Pontifical Catholic University of Rio de Janeiro*

**Corresponding Authors:** barbosa@puc-rio.br, paraguassu@esp.puc-rio.br, lucaabrahao@aluno.puc-rio.br

Using concepts of stochastic thermodynamics, we investigate the apparent violations of the second law of thermodynamics in the work done by a quantum system on a classical particle. This investigation is conducted in a semiclassical regime, where stochastic noise appears in the dynamics of the classical particle due to the quantum-classical interaction.

**8**

## Optical control of the time-crystalline phases in a polariton condensate with a mechanical clock

**Authors:** Dimitri Chafatinos[1]; Alejandro Fainstein[2]

[1] *IB - CAB / INN / CONICET*

[2] *IB - CAB / INN*

**Corresponding Authors:** dchafatinos@gmail.com, alex.fainstein@gmail.com

Time crystals (TCs) are many-body systems that display spontaneous breaking of time translation symmetry. Microcavity exciton-polaritons are bosonic quasiparticles resulting from the strong coupling between excitons and photons in a driven-dissipative open system and exhibit a transition to a nonequilibrium Bose-Einstein condensate state. The platform for this study is a polaromechanical (Ga,Al)As microcavity, where micrometer traps confine polaritons and $\sim$ 20GHz mechanical vibrations that are very efficiently coupled. Polaritons exhibit a pseudospin degree of freedom, with its dynamics manifested through the polarization of the emitted light. Recently, under nonresonant continuous wave excitation, a robust time crystal behavior of the polariton condensate was observed: spontaneous and stable oscillation in the spinor dynamics occurs and locks to the rhythm of the GHz-cavity phonons. Different time-crystalline phases were observed as a function of the applied laser excitation power: i) Larmor-like precession of the condensate pseudospins; ii) locking of the precession frequency to self-sustained coherent phonons; and iii) doubling of the TC period by phonons.

In this work, we demonstrate the tuning of the time-crystalline phases in a polariton state of a micrometer trap, through two additional control parameters, that evidence and exploit the critical role of the exciton reservoir that feeds the polariton condensate in the trap. Namely, i) the polarization ellipticity of the continuous wave excitation laser, that is able to induce a spin imbalance in the reservoir and thus induce a synthetic magnetic field affecting the condensate; and (ii) the position of the excitation spot laser respect to the trap, which determines the spatial distribution of the reservoir and is shown to favor a mechanically driven dynamics of the reservoir. These results establish microcavity polaritons affected by mechanics as a platform for the investigation of time-broken symmetry in nonhermitian systems. In addition, it is argued that the mechanically induced time modulation of the coupling between spinor modes could be used to control quantum gates based on polariton fluids proposed for classical and quantum computing.

**9**

## Quantum Communications in Optical Fibers

**Author:** Freddy Herrera Cueva[1]

[1] *Amherst College*

**Corresponding Author:** fherreracueva25@amherst.edu

Quantum communications in optical fibers are a fundamental building block for the development of a future quantum internet. A key advantage of this approach is scalability, as photons can be easily generated, manipulated, and detected in large quantities, which facilitates the design of complex quantum networks. In addition, optical fibers can transmit photons over long distances with minimal loss and noise, which is essential for preserving the delicate quantum states of photons as qubits.

Entangled photon-pair sources based on spontaneous parametric processes are widely used in quantum information experiments, including this presentation. Our efforts were directed to measure, characterize, and optimize the nonlinear effects of two-photon interference (TPI) based phenomena

in an optical communication setup. For this, we propose a model that allows us to quantify the effects of the generation of multiple entangled photon pairs on visibility and coincidence-to-accidental ratio (CAR) measurements as our communication quality parameters.

**10**

# Tsallis and Shannon permutation entropies in semiclassical systems

**Author:** GASPAR GONZALEZ[1]

[1] *Instituto de Física de La Plata*

**Corresponding Author:** gaspar.ag.acosta@gmail.com

We analyze semiclassical systems (conservative and dissipative ) with Tsallis permutation entropy. In this type of systems, classical and quantum variables interact. We study the classical limit in function of a motion invariant related to the uncertainty principle. We find interesting results in the convergence process. We compare with Shannon permutation entropy.

**11**

# Non-hermitian zigzag Glauber lattice

**Authors:** Braulio Misael Villegas Martínez[1]; Gilberto Sebastián Fahara Ojeda[1]

**Co-authors:** Jacob Licea-Rodríguez [1]; Jesús Escobedo Alatorre [1]; José Javier Sánchez Mondragón [2]; Roberto Alan Beltrán Vargas [1]; Sandra Gesing [3]

[1] *Centro de Investigación en Ingeniería y Ciencias Aplicadas (CIICAp)*

[2] *Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)*

[3] *San Diego Supercomputing Center (SDSC)*

**Corresponding Authors:** gilberto.faharaoje@uaem.edu.mx, roberto.beltran@uaem.mx, jescobedo@uaem.mx, sgesing@sdsc.edu, braulio.villegas@uaem.mx, jacob.licea@uaem.mx, jsanchez@inaoep.mx

This work aims to study the dynamics of a non-Hermitian zigzag waveguide array configuration consisting of two interleaved one-dimensional (1D) waveguides. In this configuration, one layer forms a scalene triangle with two adjacent waveguides in the lower layer. The proposed photonic lattice model is semi-infinite and composed of single-mode waveguides, with the propagation constants $\lambda n$, varying linearly with the waveguide number $n$. This model is a variant of the semi-infinite Glauber-Fock lattice, characterized by hopping amplitudes that increase with the square root of the site number, $\alpha_2\sqrt{n+1}$ and $\alpha_1\sqrt{n}$. Here, $\alpha_2$ and $\alpha_1$ are constants representing the site-independent forward and backward hopping amplitudes between two adjacent waveguides in the neighboring layer. The scalene arrangement of these waveguides results in unequal forward and backward hopping amplitudes, while the hopping amplitude for the next-nearest-neighbor waveguides within the same layers is denoted by $\beta$. The modal field amplitude of light, $\Psi_n(Z)$, in the non-Hermitian lattice satisfies the differential equation set [1]

(1)

$$\&i\frac{d}{dZ}\Psi\_n(Z)+\lambda n\Psi\_n(Z)+\alpha\_1\sqrt{n}\Psi\_n-1(Z)+\alpha\_2\sqrt{n+1}\Psi\_n+1(Z) \quad (2)$$

$$\& \quad (3)$$

$$+\beta\left[\sqrt{n(n-1)}\Psi\_n-2(Z)+\sqrt{(n+1)(n+2)}\Psi\_n+2(Z)\right]=0,\quad n=0,1,2,... \quad (1)$$

(4)

satisfying $\Psi_n(Z)=0$ for $n<0$. To obtain the analytical solution describing the evolution of non-classical light in the aforementioned waveguide system, it is convenient to use a simplified notation in which each single-mode waveguide is arranged in a vector given by $|\psi\,(Z)\rangle=\sum_{n=0}^{\infty}\Psi_n(Z)|n\rangle$. Here, $|n\rangle$ plays a role analogous to Fock states and corresponds to a situation where only the waveguide with the number $n$ is excited. In this form, Eq.(1) can be rewritten in a Schrödinger-like equation form

$$i\frac{d}{dZ}|\psi\,(Z)\rangle=-\left[\lambda\hat{n}+\alpha\_1\hat{a}\hat{}\dagger+\alpha\_2\hat{a}+\beta\left(\hat{a}\hat{}\dagger 2+\hat{a}\hat{}2\right)\right]|\psi\,(Z)\rangle, \quad (2)$$

where $\hat{a}^\dagger$ and $\hat{a}$ denote the bosonic creation and annihilation operators in the waveguide number basis, acting as $\hat{a}^\dagger|n\rangle=\sqrt{n+1}|n+1\rangle$ and $\hat{a}|n\rangle=\sqrt{n}|n-1\rangle$. In this context, time plays the role of the propagation distance, i.e., $t=-Z$. One can easily prove that if the proposed $|\psi\,(Z)\rangle$ is substituted into Eq.(2) the system described by Eq.(1) is recovered. Therefore, we can solve Eq.(2) instead of Eq.(1). Additionally, note that the Hamiltonian involved in the Schrödinger-like equation is non-Hermitian. To address this, we implemented a change of variable $|\psi\,(Z)\rangle=\hat{U}_1^{-1}|\phi\,(Z)\rangle$ using the non-unitary transformation $\hat{U}_1=\exp\left(\gamma_1\hat{a}^\dagger-\gamma_2\hat{a}\right)$, where $\gamma_1=\frac{2\beta\alpha_2-\lambda\alpha_1}{4\beta^2-\lambda^2}$ and $\gamma_2=\frac{2\beta\alpha_1-\lambda\alpha_2}{4\beta^2-\lambda^2}$. This transformation corresponds to a non-Hermitian displacement operator structure akin to Glauber-like displacement operators [2,3]. Moreover, such transformation allows us to obtain a Hermitian propagation described by the new Schrödinger-like equation in terms of $|\phi\,(Z)\rangle$

$$i\frac{d}{dZ}|\phi\,(Z)\rangle=-\left[2\beta\left(\hat{K}\hat{}++\frac{\lambda}{\beta}\hat{K}\hat{}0+\hat{K}\hat{}-\right)-f\right]|\phi(Z)\rangle, \quad (3)$$

being $\hat{K}^+=\frac{\hat{a}^{\dagger 2}}{2}$, $\hat{K}^0=\frac{(\hat{n}+1/2)}{2}$, $\hat{K}^-=\frac{\hat{a}^2}{2}$ and $f=\frac{2\alpha_1\alpha_2\left[\lambda-\beta\left(\frac{\alpha_1}{\alpha_2}+\frac{\alpha_2}{\alpha_1}\right)\right]+\lambda\left(\lambda^2-4\beta^2\right)}{2(\lambda^2-4\beta^2)}$. It is important to mention that the above non-unitary transformation naturally induces Hermitian dynamics resembling a squeezed-like photonic lattice [4]. In the optical context, such a transformation results in a reciprocal optical lattice for which exact solutions of the corresponding dynamical equations can be easily obtained. By using the inverse transformation to find the original solution $|\psi(Z)\rangle$, after performing algebraic steps as outlined in reference [5] and assuming that the light is injected into $n$-th waveguide, i.e. $|\psi(0)\rangle=|n\rangle$, the light amplitude in $m$-th site, $\Psi_{n,m}\,(Z)=\langle m|\psi(Z)\rangle$, is given by

$$\Psi\_n,m\,(Z)=\exp\left(-i\frac{\nu}{2}\right)\sum\_k=0\hat{}\infty\mathfrak{S}m,k(Z)\,\mathfrak{d}\mathrm{m,k}(Z)\,\mathfrak{d}m,k(Z)\,\mathfrak{d}\mathrm{m,k}(Z)\,\mathfrak{d}k,n\,(Z)\,,(4)$$

where

$$=\&\sqrt{m!k!}\left(\frac{g\_1}{2}\right)\hat{}\frac{m+k}{2}\exp\left(\frac{g\_2}{4}\right) \quad (9)$$

$$\sum m,k(Z)\ =\&\sqrt{m!k!}\left(\frac{g\_1}{2}\right)\hat{}\frac{m+k}{2}\exp\left(\frac{g\_2}{4}\right)\sum\mathrm{m,k}(Z)\ =\&\sqrt{m!k!}\left(\frac{g\_1}{2}\right)\hat{}\frac{m+k}{2}\exp\left(\frac{g\_2}{4}\right)\sum m,k(Z)\ =\&\sqrt{m!k!}\left(\frac{g\_1}{2}\right)\hat{}\frac{m+k}{2}\exp\left(\right.$$

$$\nu(Z)=\&\frac{1}{\Gamma\left(\lambda+2\alpha\_2\right)}\left\{2f\left(\lambda+\beta\right)\Gamma Z-2\alpha\_1\alpha\_2\frac{\left(\lambda-2\beta\frac{\alpha\_2}{\alpha\_1}\right)\left(\lambda-2\beta\frac{\alpha\_1}{\alpha\_2}\right)}{\left(\lambda-2\beta\right)\left(\lambda\hat{}2-4\beta\hat{}2\right)}\left[\lambda+\beta\left(\frac{\gamma\_1}{\gamma\_2}+\frac{\gamma\_2}{\gamma\_1}\right)\right]\sinh\left(\Gamma Z\right)\right\},$$

and provides the corresponding exact analytical solution of the Schrödinger-type Eq.(2), applicable specifically when $\lambda \neq -2\beta$. This solution is not documented in the existing literature until now. The comparison of light intensity propagation, $I(Z) = |\Psi_{n,m}(Z)|^2$, obtained by numerically solving Eq.(1) and evaluating the exact analytical solution Eq.(5), in the regime $\lambda > \beta$, will be presented during the poster session. Specifically, we will discuss the scenario of non-Hermitian Bloch oscillations.

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**12**

# Selective Parameter Estimation in Quantum Sensing: A Paradigmatic Study Using Non-Uniform Dynamical Decoupling Sequences and a 3-Dimensional Semiclassical Bath Model

**Authors:** Francisco Valentín Pereyra Aponte[1]; Gonzalo Agustín Álvarez[2]; Martín Kuffer[3]; Maximiliano Gatto[1]

[1] *Instituto Balseiro, CNEA, Universidad Nacional de Cuyo*

[2] *Instituto Balseiro, CNEA, Universidad Nacional de Cuyo - Centro Atómico Bariloche, CONICET, CNEA - Instituto de Nanociencia y Nanotecnologia, CNEA, CONICET*

[3] *Instituto Balseiro, CNEA, Universidad Nacional de Cuyo - Centro Atómico Bariloche, CONICET, CNEA - Instituto de Nanociencia y Nanotecnologia, CNEA, CONICET*

**Corresponding Authors:** gonzalo.alvarez@ib.edu.ar, maximiliano.gatto@ib.edu.ar, martin.kuffer@ib.edu.ar, francisco.pereyra@ib.edu.ar

Quantum sensing offers powerful techniques for extracting environmental information at atomic and nanoscale levels, with selective parameter estimation being crucial in complex environments. In this study, we investigate a nuclear spin-1/2 qubit sensor interacting with a three-dimensional bath characterized by multiple spectral densities and asymmetric system-environment interactions, aiming to determine key bath parameters with minimal measurements. These parameters include the asymmetry morphology, corresponding correlation times, and long-time stationary parameters.

Using non-uniform dynamical decoupling sequences, we selectively filter and infer the bath parameters, focusing primarily on the correlation timescales and the spectral density long-time parameters. The ability of these sequences to minimize pulse error and target specific environmental parameters makes them ideal for this purpose. Our experimental model, employing a semiclassical bath via molecular diffusion on a white matter phantom, serves as a paradigm for representing a 3D environment with asymmetric morphology, describing it as a general quantum sensor environment.

Specifically, we apply pulse gradients in different directions to generate the asymmetry and extract the primary direction of molecular diffusion and key environmental parameters. Our results demonstrate that, with few measurements, we can determine the diffusion morphology and the appropriate diffusion model characterizing the environment. This work advances quantum sensing and provides a framework for selective and efficient environmental parameter inference in complex settings.

**13**

## Hermitian operator method and Hellmann-Feynman theorem for calculating excited-state expected values in the doubly-occupied configuration interaction space

**Author:** Adán Garros[1]

[1] *(1) Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física. Buenos Aires, Argentina. (2) CONICET - Universidad de Buenos Aires, Instituto de Física de Buenos Aires (IFIBA). Buenos Aires, Argentina.*

**Corresponding Author:** agarros@df.uba.ar

The Hermitian operator method (HOM) enables the determination of excitation energies in correlated many-particle systems using the reduced density matrices (RDMs) of a reference state [1]. Additionally, other techniques can provide precise approximations of ground state RDMs in systems with strong electronic correlations within the doubly occupied configuration interaction (DOCI) space [2]. Recently, the HOM approach has been successfully formulated in the DOCI space (HOM-DOCI), yielding highly satisfactory results [3]. The determination of excitation energies using HOM-DOCI highlights the potential to exploit the Hellmann-Feynman theorem for calculating expected values and RDMs of excited states, thus further extending its applicability. The framework and results of this extension are presented [4].

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**14**

## Electron Detatchment in Atomic Collisions

**Author:** Aldo Angel Martínez Calderón[1]

**Co-authors:** Guillermo Hinojosa [2]; Marcelo Sant'Anna [3]

[1] *Instituto de Ciencias Físicas, UNAM*

[2] *ICF, UNAM*

[3] *Instituto de Física, Universidade Federal do Rio de Janeiro*

**Corresponding Author:** amartinez@icf.unam.mx

In this poster I'd like to show how we detect electron detatchment proccesses in atomic collisions experiments. In our work, we focus on systems with oxygen and nitrogen, with projectile energies in the order of keV.

The techniques used consist of monitoring two beams resulting from the collision of the original $O^-$ beam: one of the neutralized $O$ species and one of the negative $O^-$ (and $O^{-*}$) species. The variation of the intensity of each as the number of target particles ($N_2$) increases tells us the value of the interaction area (the cross section).

The ions of the original beam are formed in an electron-enriched container and a gaseous mixture of Ar and $O_2$ inside a vacuum chamber: with the different electrodes of the particle accelerator the ions are accelerated, focused and separated so that only the $O^-$ beam enters a container and interacts with the N2 gas at controlled pressures.

**15**

## Modification of chemical reactivity via light–matter coherence

**Authors:** Felipe Herrera[1]; Felipe Recabal Rivas[1]; Johan Triana[2]

[1] *Universidad de Santiago de Chile*

[2] *Universidad Católica del Norte*

**Corresponding Authors:** johan.triana@ucn.cl, felipe.herrera.u@usach.cl, felipe.recabal@usach.cl

Experimental evidence of chemical reactivity in cavity quantum electrodynamics shows modifications of reaction rates under strong light-matter coupling in contrast with out-of-cavity scenario [1,2]. However, the development of general theories to understand and reproduce experimental measurements remains a challenge. We propose a quantum mechanical model that describes the reaction-rate suppression of up to 80% observed in experiments of phenyl isocyanate alcoholysis with cyclohexanol in a Fabry-Perot cavity [3]. We implement a Lindblad quantum master equation that describes the reactive vibrational NCO mode for an ensemble of phenyl isocyanate molecules coupled to a resonant electromagnetic cavity vacuum. Rate suppressions are predicted as a consequence of the resonant depopulation of the reactive vibrational mode, relative to a canonical Boltzmann distribution. We show that energetic disorder protects the light-matter coherences of an ensemble of molecules from many-body dilution of correlations, in agreement with recent work on disorder-assisted entanglement protection [4]. Our findings extend the understanding of cavity-modified chemistry and suggests connections with quantum science that have yet to be explored.

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**16**

## Study of correlated Stokes and anti-Stokes photon pair emission in Raman Scattering

**Author:** Filomeno Soares de Aguiar Junior[1]

[1] *D'OR Institute of Research and Education - RJ / Federal University of Rio de Janeiro - RJ (UFRJ)*

**Corresponding Author:** filomeno.sa.junior@gmail.com

The inelastic scattering exhibits two components, Stokes (S) and anti-Stokes (aS), which are extensively explored in spectroscopy as the vibrational fingerprints of materials. In Stokes scattering, a photon from the laser loses energy, creating a vibrational excitation. In anti-Stokes scattering, the vibrational energy from the molecule is consumed, resulting in the scattering of a higher-energy photon. As proposed by Klyshko in 1977 [1], these two processes can occur simultaneously within the vibrational lifetime, producing correlated Raman scattering. In this case, a correlated S-aS photon pair is created through an energy exchange between the S and aS scattering, which can be mediated by a real or virtual excitation analogous to the Cooper pair in superconductivity [2]. The "real"SaS process and the "virtual"process, related to the photonic Cooper pair, have been observed in various transparent materials, including solids like diamond [3] and liquid samples such as water [4] and hydrocarbons [2]. From a spectroscopy perspective, efficient SaS processes should be considered in Raman spectroscopy as they can lead to the observation of nonlinear anti-Stokes signals. However, like the Raman signal, the intensity of the SaS process is very weak, and achieving a high number of correlated S-aS photons is still a challenge. In this poster I will present the main results from the study of the SaS process in transparent samples, focusing on recent findings with decane molecules [5].

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**17**

# Quantum Nonlocality and Contextuality with Photonic Circuits

**Authors:** Luiz Henrique Peres Siqueira[1]; Pierre-Louis de Assis[1]

[1] *University of Campinas (UNICAMP)*

**Corresponding Authors:** lpesi@ifi.unicamp.br, plouis@ifi.unicamp.br

Quantum entangled particles have been shown to manifest correlations irreproducible in the classical world. Such correlations, usually detected via violation of Bell Inequalities, serve as a path to deepen our knowledge of Nature, while also having concrete applications in quantum information theory and cryptography. In this work, I discuss how nonlocality and contextuality tests may be individually and simultaneously performed in reconfigurable photonic integrated circuits with path-encoded single photons.

**18**

# Quantum Vacuum Sagnac Effect

**Author:** Guilherme Matos[1]

**Co-authors:** François Impens [1]; Paulo Maia Neto [1]; Reinaldo de Melo e Souza [2]

[1] *Universidade Federal do Rio de Janeiro*

[2] *Universidade Federal Fluminense*

**Corresponding Authors:** reydmelo@gmail.com, impens@if.ufrj.br, pamn@if.ufrj.br, gcosta@if.ufrj.br

We report on the quantum electrodynamical analog of a Sagnac phase induced by the fast rotation of a neutral nanoparticle onto atomic waves propagating in its vicinity. The quantum vacuum Sagnac phase is a geometric Berry phase proportional to the angular velocity of rotation. The persistence of a noninertial effect into the inertial frame is also analogous to the Aharonov-Bohm effect. Here, a rotation confined to a restricted domain of space gives rise to an atomic phase even though the interferometer is at rest with respect to an inertial frame. By taking advantage of a plasmon resonance, we show that the magnitude of the induced phase can be close to the sensitivity limit of state of the art interferometers. The quantum vacuum Sagnac atomic phase is a geometric footprint of a dynamical Casimir-like effect.

**19**

## Characterization of thermal refractive noise in silicon nitride microcavities

**Authors:** Gabriel Couto Rickli[1]; Yuri Sacha Correa Lopes da Silva[1]

**Co-authors:** Alexander L. Gaeta [2]; Marcelo Martinelli [1]; Michal Lipson [2]; Nathalia Thomazio [1]; Paulo A. Nussenzveig [1]; Renato R. Domeneguetti [3]; Roger Kogler [4]; Xingchen Ji [2]

[1] *Universidade do Estado de São Paulo (USP)*

[2] *Columbia University*

[3] *Technical University of Denmark*

[4] *Humboldt Universität*

**Corresponding Authors:** gabrielrickli@gmail.com, ntomazio@if.usp.br, yurisacha.silva@usp.br, rogerkogler@alumni.usp.br, mmartine@usp.br

This study examines the temperature-dependent excess phase quadrature noise in a microchip-based optical parametric oscillator (OPO). The investigation focuses on the correlation between temperature variations and added phase quadrature noise to enhance the OPO's performance for applications including entangled light generation.

**20**

## Quantum teleportation protocol in continuous variables between different wavelenghts

**Authors:** Felipe Lucas Gewers[1]; Beatriz Vilela de Moura[1]; Gabriel C. Borba[1]; Igor Konieczniak[2]; Paulo A. Nussenzveig[1]; Marcelo Martinelli[1]

[1] *USP - Universidade de São Paulo*

[2] *UFPR - Universidade Federal do Paraná*

**Corresponding Author:** biamoura@usp.br

The teleportation protocol is a very important tool for quantum computation. It is useful not only for secure communication, but also as a form of quantum processing. The aim of this work is to explore multicolor quantum teleportation, more specifically with 795 nm and 1608 nm beams. The first corresponds to the D1 line of $^{87}$Rb atoms, that presents uses as memory, and the second is in the range of telecom L-band.

**21**

## Formulation of Optomechanical Interaction and Inverse Design

**Author:** Ian carlo Parra Alzate[1]

**Co-author:** Thiago Alegre [1]

[1] *Unicamp*

**Corresponding Authors:** alegre@unicamp.br, i272544@dac.unicamp.br

Cavity optomechanics is a very interesting field for large variety of applications: microwave signal conversion, fundamental physic platform, quantum information processing, etc. These applications

were often developed within micro-fabricated devices with high quality factors and allowing high electromagnetic energy concentration circulating within de cavity. This is due to the superposition of both mechanical and optical modes. Controlling the light-matter interaction can be difficult and it can be done, e.g, by varying the refraction index over the all structure. Usually, the design of such devices is based on simulation and fitting of some variables of interest within a large parameter space that describes the physics involved. Moreover, the fabricated structure has defects or imperfections which depend on the fabrication technique. In order to deal with these problems, in the last years it was developed a methodology of design called inverse design. This technique employs both simulation (e.g, Maxwell Equations) and optimization of some parameters of interest (e.g, refraction index) for getting a fabricable device. We can also specify the functionality of the device (e.g, beam splitter, beam switch, etc) and experimental constraints (e.g, minimum feature size). We are interested in presenting a fundamental description of optomechanical interaction and how we are pretending to use the inverse design strategy to optimize this interaction between phonons and photons, which is an unresolved optimization problem nowadays and we believe it can be a revolutionary and new understanding in this field. On the other hand, non-intuitive new structures and behaviour can be derived from this kind of inverse design problem.

**22**

## Entanglement of three indistinguishable particles

**Author:** Paula Céspedes[1]

**Co-authors:** Federico Holik [2]; Ana Majtey [1]

[1] *Instituto de Física Enrique Gaviola - Conicet*

[2] *Instituto de Física La Plata - Conicet*

**Corresponding Author:** paulacespedes@unc.edu.ar

Although the definition of entanglement for distinguishable particles is well understood, the notions of entanglement and non-locality in systems of indistinguishable particles (where the (anti)symmetrization postulate must be used) are difficult to define, and several different approaches have been proposed to address this issue. In this work we study the problem of detecting tripartite entanglement among indistinguishable bosonic particles using a procedure based on the analysis of single particle properties. Specifically, we follow the entanglement criterion for two indistinguishable particles proposed by Ghirardi et. al. (2002) and extend the argument to systems of three indistinguishable bosonic qubits and qutrits. By analysing representative examples, we found states that are qualitatively different from the two particle case. Our results contribute to the development of a comprehensive criterion for the entanglement of three indistinguishable particles.

**23**

## Excitation of traveling surface acoustic waves in Lithium Niobate waveguides through backward stimulated Brillouin scattering.

**Author:** Felipe J. L. dos Santos[1]

**Co-authors:** Caique C. Rodrigues [1]; Nick J. Schilder [1]; Roberto O. Zurita [1]; Letícia S. Magalhães [2]; Amirhassan Shams-Ansari [2]; Thiago P. M. Alegre [1]; Marko Lončar [2]; Gustavo S. Wiederhecker [3]

[1] *Universidade Estadual de Campinas - UNICAMP, Campinas, SP, Brazil*

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

[3] *Universidade Estadual de Campinas, Campinas, SP, Brazil*

**Corresponding Author:** santosfl@ifi.unicamp.br

Stimulated Brillouin Scattering (SBS) is a third-order nonlinear optical process which mediates the interaction between photons and phonons. SBS has been used in quantum level operations to bosonic systems such as single-phonon addition and subtraction to a mechanical thermal state. We've measured mechanical frequencies around 7.5GHz from traveling waves through backward SBS in Lithium Niobate on Insulator waveguides (LNOI). This was one of the first SBS measurements on this material. We've explored Lithium Niobate anisotropic characteristics, and observed clear on-chip Brillouin signal in orthogonal polarizations. Finally, we've evaluated the Brillouin gain as a function of the orientations of the waveguides, and successfully quantified gains up to $82\,\mathrm{m}^{-1}\,\mathrm{W}^{-1}$.

**24**

## Towards quantum state reconstruction of mechanical states in lithium niobate devices

**Authors:** Otávio Paiano[1]; Gustavo Wiederhecker[1]

[1] *Universidade Estadual de Campinas*

**Corresponding Author:** ompaiano@ifi.unicamp.br

Lithium niobate devices are promising platforms for the study of non-classical mechanical states and the development of quantum acoustic technologies due to their strong piezoelectric and photoelastic effects. The latter allows probing the mechanical state of a system before and after opto-mechanical interactions. For instance, Brillouin scattered photons may act as messengers for the interaction, indicating the addition (Stokes) or subtraction (anti-Stokes) of a phonon to the mechanical system. One powerful technique to retrieve the quantum state of the mechanical systems modified through the interaction with light is quantum state tomography. In this technique, the quantum state is the solution of an inverse problem that takes the measurements as an input. Here we explore available algorithms to solve the associated inverse problem and discuss the prospects of lithium niobate devices. Regarding the reconstruction algorithms, we outline the advantages of the iterative Maximum Likelihood method over the typical inverse Radon transformation.

**25**

## Dark Resonances as Probes: Measuring the Rotational Doppler Effect with a Single Ion

**Authors:** Nicolas Adrian Nuñez Barreto[1]; Muriel Bonetto[1]; Marcelo Luda[1]; Cecilia Cormick[2]; Christian Schmiegelow[None]

[1] *Universidad de Buenos Aires*

[2] *FAMAF*

**Corresponding Authors:** nnunez@df.uba.ar, cecilia.cormick@unc.edu.ar, marceluda@gmail.com, mbonetto@df.uba.ar, schmiegelow@df.uba.ar

We present an experiment investigating the rotational Doppler effect using a single trapped ion excited by two co-propagating vortex laser beams. The setup isolates the azimuthal gradients of the fields, eliminating longitudinal and curvature effects. We provide a detailed characterization of the phenomenon by deterministically positioning a single ion across the beams, achieving a signal which depends on the angular velocity of the ion and the difference of optical orbital angular momentum between the two beams. Our results reveal key properties of the rotational Doppler effect, showing its divergence approaching the center of the beam. This offers insights into the feasibility of super-kicks or super-Doppler shifts for sensing and manipulating atomic motion transverse to the beams' propagation direction

**26**

## Towards motion and temperature measurement and control of levitated nanoparticles.

**Author:** Lucas Mendicino[1]

**Co-authors:** Christian Schmiegelow [1]; Franco Mayo [1]; Santiago Gliosca [1]

[1] *Instituto de física de Buenos Aires, Departamento de Física, Universidad de Buenos Aires*

**Corresponding Authors:** lmendicino@df.uba.ar, fmayo@df.uba.ar, smgliosca@gmail.com, schmiegelow@df.uba.ar

We present our advances in trapping and controlling the external degrees of freedom of $Er^{3+}Yb^{3+}$:$NaYF_4$ nano-crystals confined in a Paul trap, which are particles intended for spectroscopy experiments. Additionally, we outline advancements in the theoretical understanding of cooling $Yb^{3+}$:$NaYF_4$ nanoparticles, aiming to devise strategies to surpass current cooling limits for these systems.

Our experimental advances towards controlling the external degrees of freedom of a levitated nanoparticle via laser sensing include the characterization of the motion of individual $Er^{3+}Yb^{3+}$:$NaYF_4$ nano-particles trapped in a quadrupole Paul trap under various pressures and trapping parameters. Also, we measured the spectra of clusters of nano-particle samples deposited on an aluminum sheet as we varied the temperature under ambient pressure.

Theoretically we develop strategies for enhancing the cooling efficiency or achieving a lower temperature, we analyze the $Yb^{3+}$ embedded in a nano-crystal system using quantum mechanics formalism. We conduct numerical simulations integrating experimental data to estimate decay rates proportional to the emission cross-section of each resonant line at various temperatures. We demonstrate that a multi-wavelength scheme alone is not a feasible strategy. However, based on these results, we investigate how adjusting the strength of specific emission lines through the Purcell effect can improve cooling efficiency.