THE 29TH CENTRAL EUROPEAN WORKSHOP ON QUANTUM OPTICS CEWQO29, VILNIUS, LITHUANIA

23 - 27 JUNE 2025

ABSTRACT BOOK

INVITED TALKS

Hybrid State Discrimination Strategy Exploiting Classical And Nonclassical Features

L. Razzoli[1], **A. Pozzoli**[1], **A. Allevi**[1]

[1] *Department of Science and High Technology, University of Insubria, Via Valleggio 11, I-22100 Como (Italy)*

In communication protocols, the discrimination of the alphabet in which a message is encoded represents a fundamental step. Depending on the complexity of the message and the security of the transmission channel, different strategies can be employed [**1**]. Over the years both direct and homodyne detection systems have been widely used for this purpose [**2**, **3**]. More recently, hybrid detection schemes, combining photon-number-resolving (PNR) detectors with interferometric setups, have been developed and successfully implemented, thus enabling the exploitation of both discrete and continuous variables [**4**].

In most cases, optical communication protocols involve coherent states of light due to their relative robustness compared to nonclassical states. Nevertheless, the use of quantum resources could improve the security of the transmission channels by enabling the detection of eavesdropping attempts. This result could be achieved thanks to the exploitation of mesoscopic quantum states, which are robust against loss and noise [**5**].

Here we consider a communication protocol, whose transmission channel is based on mesoscopic twin-beam (TWB) states and the alphabet used to encode information consists of two thermal signals with different mean values, superimposed on a portion of the TWB state [**6**]. This kind of information is transmitted by Alice, the sender, to Bob, whose receiver is equipped with PNR capability. In particular, we investigate the potential of a hybrid discrimination strategy based on the combination of the information extracted by classical (the mean value) and nonclassical (the noise reduction factor) features [**7**].

The reliability of the proposed method is assessed in terms of error probability and through the application of a binary classifier, which offers additional insight into the types of errors occurring in the communication process. The investigation is performed as a function of the size of the data samples used to encode the message bits, a critical parameter that significantly impacts the performance of the system. The obtained results open new perspectives in the use of mesoscopic quantum resources to improve the security of communication channels.

References

[1] G. Cariolaro, *Quantum Communications* (Springer International Publishing, 2015).

[2] E.Diamanti, H.-K.Lo, and B.Qi, Npj Quantum Inf. **2**, 16025 (2016).

[3] S. Olivares, S. Cialdi, and F. Castelli, Phys. Rev. A **87**, 050303 (2013).

[4] A. Sanvito, S. Cassina, M. Lamperti, M. N. Notarnicola, S. Olivares, and A. Allevi, Opt. Express **32**, 39846-39859 (2024).

[5] A. Allevi and M. Bondani, Opt. Express **29**, 32842-32852 (2021).

[6] A. Allevi and M. Bondani, Sci. Rep. **12**, 15621 (2022).

[7] L. Razzoli, A. Pozzoli, and A. Allevi, manuscript in preparation.

Intertwined entanglement in topological pumps

Tilman Esslinger

ETH Zurich

We create spatially separated Bell pairs from double occupancies in a fermionic lattice gas using a bidirectional Thouless pump. By controlling the interaction, exactly one atom of the double occupancy occupies the lower and the other the upper band of the topological pump, each experiencing opposite Chern numbers. Topological pumping therefore transports the two correlated components in opposite directions, further separating them with each pumping cycle. During the pumping we apply SWAP gates, which allow the entangled pairs to pass through each other, giving rise to intertwined entanglement over many lattice sites. As a result, we observe distinctive frequencies and multi-frequency patterns in singlet-triplet oscillations. Perspectives of the scheme for quantum computation, simulation and sensing will be discussed [1,2].

References

[1] Z. Zhu, Y. Kiefer, S. Jele, M. Gächter, G. Bisson, K. Viebahn, T. Esslinger, https://arxiv.org/abs/2409.02984

[2] Z. Zhu, M. Gächter, A.-S. Walter, K. Viebahn, T. Esslinger, Science 132, 317 (2024)].

Preparation and Characterization of non-Gaussian Quantum States of Motion in a Mechanical Resonator

Matteo Fadel *1

1 *ETH Zürich, 8093 Zürich, Switzerland*
*contact: fadelm@phys.ethz.ch

Circuit quantum acoustodynamics (cQAD) integrates mechanical resonators with superconducting circuits, combining the high-quality factor and compact footprint of mechanical modes with the strong nonlinearity of Josephson junctions. This platform, therefore, holds potential applications in quantum technologies, such as quantum simulations and quantum sensing using mechanical degrees of freedom. However, unlocking such applications requires the development of a toolbox for preparing and manipulating the resonator's mechanical states of motion.

In my talk, I will first present our recent results on realizing a squeezing interaction in the mechanical resonator through parametric driving of the coupled qubit [1]. This coupling also induces an inherited Kerr-type nonlinearity in the mechanical mode, enabling the preparation of non-Gaussian states of motion, see Fig. 1a. I will then discuss the preparation of non-Gaussian states of motion using optimal control techniques [2]. Specifically, I will demonstrate the preparation of multi-phonon Fock states, see Fig. 1b/c, which we characterize using criteria that quantify their quantum non-Gaussianity and their metrological advantage.

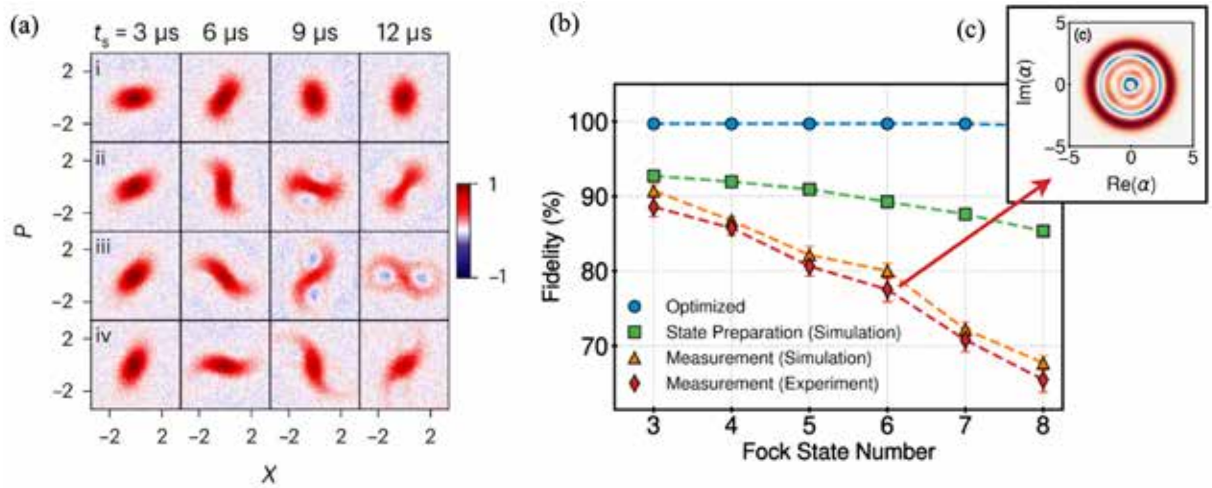


Fig. 1: Preparation of non-Gaussian states of motion. (a): state evolution in a squeezed nonlinear mechanical oscillator, leading to quantum states exhibiting negative regions in the Wigner function [1]. **(b,c):** preparation of multi phonon Fock states using optimal control techniques [2].

[1] "Quantum squeezing in a nonlinear mechanical oscillator", S. Marti *et al.*, Nature Physics **20** 1448 (2024).

[2] "Genuine quantum non-Gaussianity and metrological sensitivity of Fock states prepared in a mechanical resonator", Q. R. Rahman *et al.*, arXiv:2412.20971 (2024).

Collective light matter interactions in free-space atomic ensembles

I. Ferrier-Barbut[1]
[1] *Laboratoire Charles Fabry, Institut d'Optique Graduate School, CNRS, Universit'e Paris Saclay*

The understanding of the cooperative emission of light by an ensemble of atoms in free space has beed an outstanding problem of atomic physics for decades. This driven-dissipative many-body system poses an outstanding challenge to theory and requires dedicated experiments. I will present experimental results from our group where we study the cooperative interaction of ensembles of cold atoms in free space with resonant radiation. First, by measuring the photons radiated by an atomic cloud that is resonantly driven by a laser, one can retrieve the existence of high-order correlations in the steady-state, due to light-induced resonant dipole-dipole interactions. Second, by using the tools of single-atom manipulation and readout, one can measure the effect of cooperative scattering by an ordered array, now at the single atom level to unravel the microscopic mechanisms behind collective effects.

Emergence of Quantum Coherence

Radim Filip[1]

[1]*Department of Optics, Faculty of Science, 17. listopadu 1192/12, 77146 Olomouc, Czech Republic*

Initially, we will present the emergence of single-qubit coherence in various regimes at low temperatures. A typical setup for generating coherence in a qubit, which is a two-level system, or its ensemble, requires a classical coherent external input to drive the system, often resulting in the linearisation of the dynamics. Here, we utilise the low-temperature limit of an oscillator coupled to the qubit to generate qubit coherences with any external drive, purely from the symmetry-broken subsystem interactions. Various models can be implemented on different experimental platforms, such as trapped ions, superconducting circuits, or solid-state qubits, to study their qubit transients and steady states. We demonstrate how engineered nonlinear dynamics can produce significant coherence in the qubit from small incoherent thermal energy across a wide range of parameter values.

Subsequently, we address the rise of coherence in quantum non-Gaussian states, which are crucial for advancing bosonic quantum technology. Despite their significance, challenges remain in deeply comprehending them, autonomously generating and controlling them, reliably detecting them, and providing conclusive certification. We will highlight the emergence of coherence in quantum non-Gaussian systems through the cooling and decay of interacting systems to their ground state, alongside its structure. Additionally, it will illustrate that nonlinear motional couplings of atoms can give rise to coherence beyond the Gaussian approximation, stimulated by a small energy of only a few thermal quanta. Moreover, the talk will introduce a new, experimentally tested, and unpublished classification of non-Gaussian effects in the continuous variable picture, which is essential for understanding the emergent phenomena.

Vectorial light-matter interaction - imprinting polarisation textures into atoms

S. Franke-Arnold[1], K. Samanta[1], S. Svensson[1], R. Maduro[1], Jinwen Wang[2], and N. Westerberg[1]

[1] *University of Glasgow, Scotland*
[2] *Xi'An University, China*

Polarisation - while invisible to the eye - has been recognized as an important feature of light since the days of Ptolemy. Over the last decades we have gained significant control in shaping light, and in our research team we routinely design phase and polarisation structures to explore their topologies, and their interaction with matter. Electric dipole transitions are, of course, sensitive to optical polarisation, allowing us to encode optical polarisation profiles as atomic spin alignment.

Optical $\sigma_\pm$ transitions, excited by the right and left circular polarisation components of polarisation structured light, in conjunction with an external magnetic fields, can form an atomic state interferometer (shown in Fig. 1), rendering atomic interaction sensitive to the polarisation profile and allowing us to imprint optical polarisation textures onto atomic spin structures. Unlike optical polarisations, atomic spin alignments react to external fields and forces, promising applications in magnetometry [1] and inertial sensing, and vice versa allowing us to retrieve properties of the structured light via atomic absorption patterns [2].

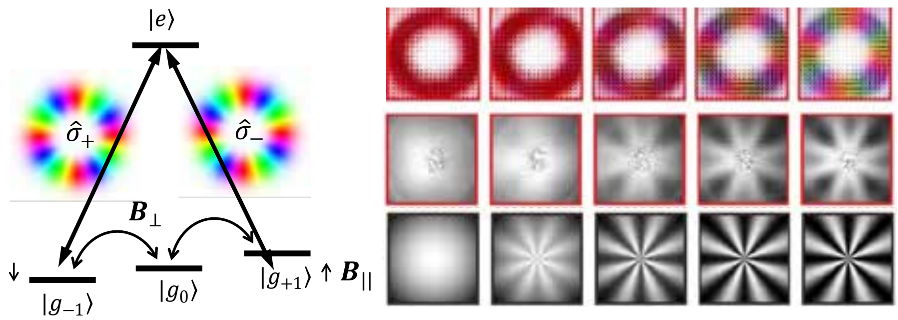


Figure 1: Left: Schematic atomic state interferometer, optically driven by orthogonal polarization components of a vector beam and by a stationary transverse magnetic field. Right: Measured polarization profiles of the probe beam, corresponding measured optical densities and theoretical predictions based on Liouville Bloch equations.

References

[1] F. Castellucci et al, Phys. Rev. Lett. **127** (23), 233202 (2021).

[2] Jinwen Wang et al, Phys. Rev. Lett. **132** (19), 193803 (2024).

Quantum information processing via on-demand light-matter interaction

Yvonne Y. Gao[1]
[1]*Centre for Quantum Technologies, National University of Singapore*

The diverse applications of light-matter interactions in science and technology stem from the qualitatively distinct ways these interactions manifest. I will present a series of experimental work that employs the light field of high-Q superconducting cavities coupled to non-linear circuit elements to harness the rich dynamics of their interactions for quantum information processing. With these versatile bosonic cQED systems, we show the ability to create, manipulate, and characterise complex non-Gaussian resource states [1] and achieve loss protection for them through phase-space engineering [2]. Moreover, by incorporating frequency-tunablility in our devices, we can effectively probe the intersections of different light-matter interaction regimes on demand [3]. Our work shows that bosonic cQED systems, albeit small in scale, provide a powerful platform to explore quantum information science and applications.

---

[1] Xiaozhou Pan, Jonathan Schwinger, Ni-Ni Huang, Pengtao Song, Weipin Chua, Fumiya Hanamura, Atharv Joshi, Fernando Valadares, Radim Filip, and Yvonne Y. Gao. Protecting the quantum interference of cat states by phase-space compression. *Physical Review X*, 13(2), 2023.

[2] Tanjung Krisnanda, Clara Yun Fontaine, Adrian Copetudo, Pengtao Song, Kai Xiang Lee, Ni-Ni Huang, Fernando Valadares, Timothy C. H. Liew, and Yvonne Y. Gao. Demonstrating efficient and robust bosonic state reconstruction via optimized excitation counting, 2024.

[3] Fernando Valadares, Ni-Ni Huang, Kyle Chu, Aleksandr Dorogov, Weipin Chua, Lingda Kong, Pengtao Song, and Yvonne Y. Gao. On-demand transposition across light-matter interaction regimes in bosonic cqed, 2023.

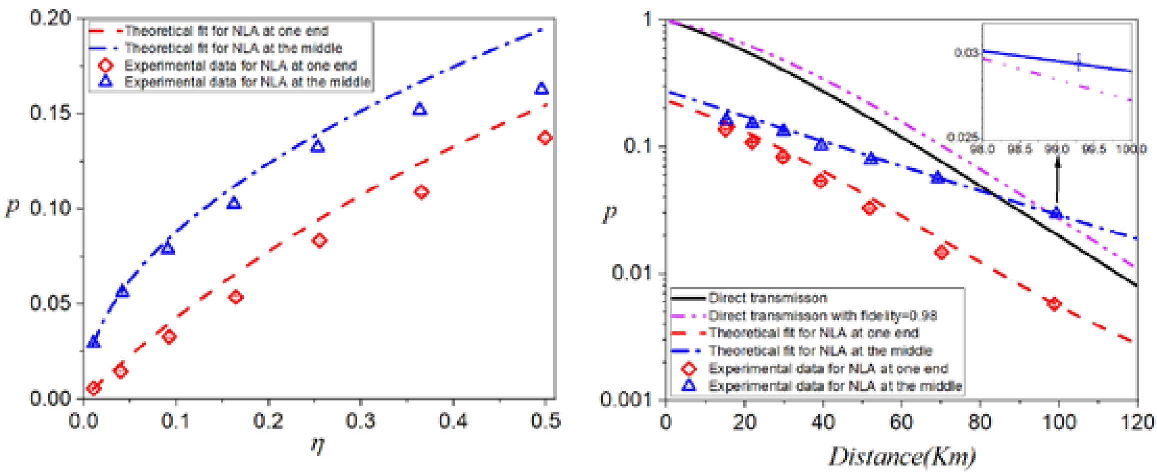
Entanglement distillation rates exceeding the direct transmission bound

Farzad Ghafari[1], Josephine Dias[2], Sergei Slussarenko[1], Timothy Ralph[2], Geoff Pryde[1]

1 Centre for Quantum Dynamics, Griffith University, Brisbane 4111, Queensland, Australia,
2 School of Mathematics and Physics, University of Queensland, St Lucia, Queensland 4072, Australia

Entanglement distribution is essential in quantum communications, underpinning secure quantum key distribution, quantum networks, and computing protocols. However, losses in optical channels, such as fiber attenuation and detector inefficiencies, significantly degrade entanglement quality and limit communication distances. Methods like quantum repeaters or advanced encoding schemes are needed to address these issues. Entanglement distillation via noiseless linear amplification (NLA) enhances entanglement quality by probabilistically amplifying quantum states without adding noise, improving the signal-to-noise ratio. By selectively amplifying successful quantum events, NLA increases entanglement fidelity and extends communication distances. NLA has emerged as an invaluable tool in quantum optics, showcasing its utility through a multitude of experimental validations [1]. These include tasks like entanglement distillation [2], entanglement purification [3], qubit amplification [4], and improved metrology [5].

Nevertheless, the no-cloning theorem confines NLA operations to probabilistic processes. Increasing the success probability of NLA is critical, as low probabilities limit practical implementation, efficiency, and scalability. Higher success rates lead to better communication efficiency, increased data throughput, and enhanced viability for real-world quantum communication.
We demonstrate a pioneering experimental protocol, strategically crafted to improve the probability of success of existing NLA protocols. We show that employing a distributed NLA protocol with a relay point positioned equidistantly between two parties (Alice and Bob) yields a better probability of success compared to employing NLA solely at Bob's end or using a recently suggested purification protocol in the majority of scenarios [6] (Left figure, comparing the probability of success (p) vs the transmissivity (η)). The direct transmission bound (PLOB bound) sets the maximum rate for exchanging quantum information without repeaters. Here, we experimentally demonstrate an NLA technique that increases the success probability in an entanglement distillation scheme, beyond the PLOB bound (Left figure, comparing the probability of success (p) vs distance in optical fibre). By demonstrating a practical, heralded noiseless linear amplification technique that surpasses this theoretical limit, the work provides critical insights and tools that can significantly enhance entanglement distribution protocols.



[1] M. Barbieri, et al. , Laser Phys. Lett. 8, 411–417 (2011).

[2] K. P. Seshadreesan, et al., Phys. Rev. A 100, 022315 (2019).

[3] A. E. Ulanov, et al. , Nat. Photonics 9, 764 (2015).

[4] S. Kosis, et al. , Nat. Phys. 9, 23 (2013).

[5] M. A. Usuga, et al., Nat. Phys. 6, 767 (2010).

[6] Mauron, et al. , Phys Rev A, 106(6), 062603 (2022).

I9

Quantum Theory of Rotor-Like Systems

Z. Hradil[1], L. Mišta, and J. Řeháček

Department of Optics, Palacký University,
17. listopadu 12, 779 00 Olomouc, Czech Republic

The talk will cover the theoretical foundations of quantum technologies that utilize complementary quantities, with a focus on exploring previously overlooked degrees of freedom. Rather than the commonly used position, momentum, or spin variables, we will concentrate on a quantum rotor, characterized by complementary quantities such as angular momentum and the unitary exponential of the angle operator [1,2]. The developed quantum theory encompasses the design of uncertainty measures based on the moment of inertia, the formulation of relevant uncertainty relations, the derivation of optimal conditions for simultaneous measurements, the identification of extremal states, and the phase space representation. The theory will be demonstrated through experiments on optimal pulse shaping and detection at the ultimate quantum limit. Additionally, we will reformulate tight uncertainty relations in the time-frequency domain and present an optimal tomography scheme to retrieve complete information about the pulse at the quantum limit.

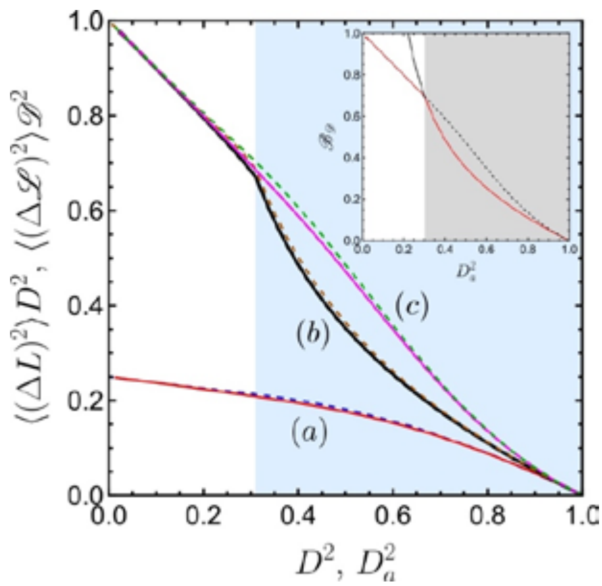


Fig. 1. Uncertainty product for variance of angular momentum and dispersion $\langle(\Delta L)^2\rangle D^2$ (a) (Heisenberg-like uncertainty) and its counterpart for simultaneous measurement (b), (c) $\langle(\Delta\mathscr{L})^2\rangle\mathscr{D}^2$, $\mathscr{D}^2 = 1-|\langle\mathscr{E}\rangle|^2$, (Arthurs-Kelly-like uncertainty) as a function of dispersion. The products are plotted for the extremal Mathieu states (solid lines) and the von Mises states (dashed lines). The pair of lines (a) shows that the von Mises states approximate the optimal Mathieu states very closely and this correspondence propagates into simultaneous measurement under various strategies. The pair of lines (b) corresponds to the numerical solutions with optimally matched Mathieu and von Mises states, and in case of (c) the signal is matched to ancilla according to the conditions saturating the Cauchy-Schwarz inequality. The inset displays the analytical solution for optimized uncertainty products, which consists from two branches, see Ref. [Mis24] for more details.

References

[1] L. Mišta, Jr. et. al., Angle and angular momentum: Uncertainty relations, simultaneous measurement, and phase-space representation, Phys. Rev. A 106, 022204 (2022).

[2] L. Mišta, Jr. , M. Mišta, and Z. Hradil, Unifying uncertainties for rotorlike quantum systems, Phys. Rev. A 110, 032208 (2024)., arXiv:2043.02498 (2024).

Topological state transfer and PT/anti-PT symmetries in dissipatively coupled quantum networks

N. Korolkova[1], M. Thornton[1], P. de la Hoz[1], D. Mogilevtsev[2]

[1]*School of Physics and Astronomy, University of St. Andrews, St. Andrews, UK*
[2]*B. I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*

Coherent chains of interacting quantum systems represent wide classes of physical objects and are regularly used as a testbed to explore diverse effects, such as new matter phases in spin chains or in networks of photonic systems. In this work we theoretically consider chains of dissipatively coupled bosonic modes [**1**], that is, modes coupled pairwise via common Markovian reservoirs. Such systems can be, for example, realised on the platform of the integrated optical waveguides. In contrast to the normal evanescent coupling, dissipative coupling can lead to collective behaviour, maintain quantum coherence despite high level of loss and enable quantum state engineering via controlled loss mechanisms. These features can be harnessed both in classical photonic systems for optical routing or in quantum technologies realm: it has recently been used to perform state equalization and non-reciprocal propagation [**1**, **2**] or to generate photon-number squeezing and entanglement [**3**, **4**]. In this talk, we discuss various topological properties in such systems and their applications.

We start with the theory for quantum state transfer across 1D dissipatively coupled bosonic chain, where the state is protected by topological properties. We drive nearest-neighbor couplings in time and analyze the ability and robustness of the state transfer. Efficient methods for state transfer are becoming increasingly important as quantum technologies mature, for example, for creating a quantum bus in quantum computing devices.

Next we look for realization of parity-time (PT)- and anti-PT-symmetries in dissipatively-coupled bosonic chains. Together, PT- and anti-PT-symmetries provide dual perspective for exploring non-Hermitian systems (see, e. g., [**6**]), exhibiting distinct implications for energy transport and topological phenomena. Apart of fundamental interest, these PT/anti-PT properties can be exploited for quantum state engineering or for control of light transport in photonic systems to implement filters, routers, an optical equivalent of a diode or to realize other non-trivial photonic elements.

References

[1] S. Mukherjee, D. Mogilevtsev, G. Ya. Slepyan, T. H. Doherty, R. R. Thomson, N. Korolkova: Dissipatively Coupled Waveguide Networks for Coherent Diffusive Photonics. Nature Communications **8**, 1909 (2017).

[2] I. Peshko, D. Pustakhod, and D. Mogilevtsev: Breaking reciprocity by designer loss. Breaking reciprocity be designer loss, J. Opt. Soc. Am. B **39**, 1926 (2022).

[3] M. Thornton, A. Sakovich, A. Mikhalychev, J. D. Ferrer, P. de la Hoz, N. Korolkova, D. Mogilevtsev: Coherent diffusive photon gun for generating non-classical states, Phys. Rev. Applied **12**, 064051 (2019).

[4] P. de la Hoz, A. Sakovich, A. Mikhalychev, M. Thornton, N. Korolkova, D. Mogilevtsev: Integrated source of path-entangled photon pairs with efficient pump self-rejection. Nanomaterials **10**, 1952 (2020).

[5] Fan Yang, Yong-Chun Liu, and Li You, Anti-PT symmetry in dissipatively coupled optical systems. Phys. Rev. A **96**, 053845 (2017).

Photonic Interconnects: Advancing Quantum Networking for Communication and Computing

J. Laurat

Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, 4 Plance Jussieu, 75005 Paris

To advance quantum information science and technologies, a wide variety of quantum machines and protocols are being developed based on different physical systems. One of the critical challenges in scaling quantum information architectures is interconnecting these systems effectively. Achieving this requires the development of specialized photonic devices, from advancing optical memory technologies to enhancing photon extraction for qubit connectivity.

In this talk, I will provide an overview of the opportunities presented by networking, including long-distance quantum communications and distributed quantum computing. I will also present recent experimental works, which includes the realization of a quantum-bit-encoding converter, the implementation of highly-efficient quantum memories based on laser-cooled neutral atoms, and the development of nanophotonic devices aimed at improving qubit coupling.

Vortex nucleations in spinor Bose condensates under localized synthetic magnetic fields

L. -R. Liu[1], S. -C. Wu[1], T. -W. Liu[1], H. -Y. Hsu[1], T. -K. Shen[1], S. -K. Yip[2], Y. Kawaguchi[3], Y. -J. Lin[1]

[1] *Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan 10617*
[2] *Institute of Physics,Academia Sinica, Taipei, Taiwan 11529*
[3] *Department of Applied Physics, Nagoya University, Nagoya, 464-8603, Japan*

Gauge fields are ubiquitous in modern quantum physics. In superfluids, quantized vortices can be induced by gauge fields. Here we demonstrate the first experimental observation of vortex nucleations in light-dressed spinor Bose-Einstein condensates under radially-localized synthetic magnetic fields. The light-induced spin-orbital-angular-momentum coupling creates azimuthal gauge potentials $\vec{A}$ for the lowest-energy spinor branch dressed eigenstate. The observation of the atomic wave function in the lowest-energy dressed eigenstate reveals that vortices nucleate from the cloud center of a vortex-free state with canonical momentum $\vec{p} = 0$. This is because a large circulating azimuthal velocity field $\propto \vec{p} - \vec{A}$ at the condensate center results in a dynamically unstable localized excitation that initiates vortex nucleations. Our observation has reasonable agreement with the time-dependent Gross-Pitaevskii simulations.

References

[1] L. -R. Liu, S. -C. Wu, T. -W. Liu, H. -Y. Hsu, T. -K. Shen, S. -K. Yip, Y. Kawaguchi, and Y. -J. Lin, arxiv.org/abs/2403.17403 (2024).

Optical neural networks for computation and computer vision

Alexander Lvovsky
Clarendon Laboratory, University of Oxford

Optical neural networks (ONNs) harness the fundamental properties of light to enable ultrafast, energy-efficient computation, surpassing the limitations of digital-electronic systems in tasks such as large-scale matrix multiplications. By exploiting interference, diffraction, and nonlinearity, ONNs can perform parallel processing of high-dimensional data, reducing latency and power consumption. This talk explores three complementary perspectives on ONNs. First, we discuss ONN applications for machine learning and our recent results on training an ONN by propagating light backwards through its layers. Second, we show how an ONN can be applied for spatial mode decomposition of an optical field, enabling the extraction of spatial information beyond the classical diffraction limit by leveraging the quantum and classical correlations in the field. Finally, we discuss coherent Ising machines, in which an optical network with feedback finds minimum-energy gates of interacting spin systems to solve nontrivial combinatorial optimization problems. In particular, we highlight our recent findings on polarization symmetry breaking, offering a new mechanism for all-optical implementation of an Ising machine. Together, these facets illustrate the versatility and transformative potential of ONNs.

Challenges in Free Space Quantum Communication

Ch. Marquardt[1,2]

[1] *Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany*
[2] *Max Planck Institute for the Science of Light, Erlangen, Germany*

Quantum communication offers the ability to distribute quantum states for the use in quantum information processing. Particularly quantum key distribution has been studied intensively towards applications. Whereas in fiber-based quantum communication one can rely on good mode field definitions, difficulties rise from potential cross coupling with different (also classical) wavelength components in deployed infrastructure. Free space quantum communication usually enables more control about the used wavelengths and modes. However atmospheric induced distortions and Doppler effects of fast moving platforms pose different challenges. We will review those challenges for different situations from short range links, to links on aircraft and satellite-based quantum communication [1]. Particularly there is a stimulating feedback between technical challenges and fundamental questions [2,3].

References

[1] Eagle-I protocol workshop https://www.ses.com/newsroom/eagle-1-advancing-europes-leadership-quantum-communications#tab-related-eventshttps://www.ses.com/newsroom/eagle-1-advancing-europes-leadership-quantum-communications#tab-related-events

[2] K. Günthner et al., Optica 4, 611 (2017)

[3] B. Hacker et al., New Journal of Physics 25 (11), 113007 (2023)

Accelerated State Expansion of a Nanoparticle in a Dark Inverted Potential

Nadine Meyer[1,2], Grégoire F. M. Tomassi[1,2], Daniël Veldhuizen[1,2], Bruno Melo[1,2], Davide Candoli[3], Andreu Riera-Campeny[3,4], Oriol Romero-Isart[3,5], Romain Quidant[1,2]

[1]Nanophotonic Systems Laboratory, Department of Mechanical and Process Engineering, ETH Zurich, 8092 Zurich, Switzerland

[2]Quantum Center, ETH Zurich, 8083 Zurich, Switzerland

[3] ICFO – Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain

[4] Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria

[5] ICREA – Instituciò Catalana de Recerca i Estudis Avancats, Barcelona 08010, Spain

Levitated nanoparticles provide a powerful and flexible platform for quantum optomechanics, offering exceptional isolation from the environment and a simple, well-defined mode structure. Unlike clamped mechanical resonators, the absence of physical supports allows for in situ tuning of the potential landscape without the need for complex nanofabrication. This level of control makes levitated systems particularly attractive for exploring macroscopic quantum phenomena, as well as for applications in force and inertial sensing.

A key challenge in generating large quantum superposition states of massive objects is the efficient expansion of their wave packets. While free evolution leads to linear growth of the position uncertainty, an inverted harmonic potential enables exponential expansion, offering a pathway to rapidly amplify quantum fluctuations to macroscopic scales.

In this work, we demonstrate this principle experimentally by expanding the center-of-mass thermal state of a 125 nm silica nanoparticle to a position uncertainty of 43.4 nm in just 260 µs. By employing an inverted dark optical potential, we suppress heating mechanisms from photon recoil, achieving a 952-fold increase in spatial uncertainty—approaching the physical size of the particle itself. This classical state expansion represents a significant step toward realizing macroscopic quantum superpositions at previously inaccessible mass and length scales.

[1] G.F.M.Tomassi et al., arXiv:2503.20707v1

I16

Quantum dot-based non-classical light sources for quantum cryptography applications at telecom wavelengths

A. Musiał[1]

[1]*Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology, Wrocław, Poland*

Non-classical light sources find application in quantum cryptography, communication and computation. In particular, single photons are required to realize BB84 protocol, whereas pairs of entangled photons – for Ekert91 protocol implementation and 2D cluster states could constitute a scalable universal platform for quantum computing. These ideas drive search for ideal light source. The requirements include: high quality of emitted light state (single photon purity, degree of indistinguishability or entanglement), high photon generation rate and emission in the telecommunication spectral range compatible with fiber infrastructure. For practical purposes compact fiber sources operating at room temperature driven electrically and preferably compatible with Si technology platform are beneficial. Introducing these quantum devices into common use requires reducing cost of their production, repeatability, scalability, small footprint and high yield.

One of many physical systems for quantum emitters identified as promising as already fulfilling some of the abovementioned requirements, are epitaxial semiconductor quantum dots (QDs) in photonic structures [1,2]. They are advantageous when it comes to high generation rates, quality of the quantum light states independent of generation rate as well as compatibility with semiconductor technology and compactness of the source. It has also been shown that they can be efficiently coupled to single mode fibers [3,4]. Among drawbacks one can find strong interaction with the environment – epitaxial QDs are embedded in a solid state matrix, and cryogenic temperatures operation for QDs emitting in the telecommunication spectral range due to finite depth of confining potential provided by material systems providing telecom emission.

In this contribution state-of-the-art InP-based and GaSb-based QD non-classical light sources will be presented. The former includes molecular beam epitaxy grown InAs/InP QDs in cylindrical photonic structures [5,6] as well as dots fabricated by metalorganic chemical beam epitaxy in circular Bragg grating microcavities [7]. Finally, recent progress in InAs(P) QDs in zinc-blende InP nanowires (vapour-liquid-solid growth within chemical beam epitaxy approach) [8] will be reported. The antimonides-based QDs are grown via local droplet etching of AlGaSb layer with Al or Ga droplets and subsequent filling of nanoholes created in this process with (In)GaSb material [9-12]. This results in inversed geometry compared to standard QDs as well as low strain high symmetry QD geometry beneficial for generation of pairs of polarization entangled photons from biexciton-exciton cascade.

References

[1] P. Michler (ed.), *Quantum Dots for Quantum Information Technologies* (Springer, New York, 2017).

[2] P. Michler, S. L. Portalupi, *Semiconductor Quantum Light Sources* (De Gruyter, Berlin, 2024).

[3] A. Musiał et al., Adv. Quantum Technol. **3**, 2000018 (2020).

[4] L. Rickert et al., Opt. Express **31**, 14750 (2023).

[5] M. Benyoucef and A. Musiał, Chapter 18 in Photonic Quantum Technologies: Science and Applications 2 (Wiley-VCH GmbH, Hoboken, NJ, 2023).

[6] D. A. Vajner et al., ACS photonics **11**, 339 (2024).

[7] P. Holewa et al., Nat. Commun. **15**, 3358 (2024).

[8] G. Bucci at al., ACS Appl. Mater. Interfaces **16**, 26491 (2024).

[9] J. Hilska et al., Cryst. Growth Des. **21**, 1917 (2021).

[10] A. Chellu et al, APL Mater. **9**, 051116 (2021).

[11] J. Michl et al., Adv. Quantum Technol. **6**, 2300180 (2023).

[12] T. Hakkarainen et al., arXiv preprint arXiv:2404.06083 (2024).

Central European Workshop on Quantum Optics (CEWQO29)

Critical parametric sensing with a Kerr superconducting resonator

Gheorghe Sorin Paraoanu[1]

[1]*Department of Applied Physics and InstituteQ, Aalto University, Finland*

The parametrically-driven Kerr oscillator is a paradigmatic model in quantum optics. We realize this system by using a quarter-wavelength resonator shunted by a SQUID that can be modulated via a varying magnetic field. Using this device, we can map the phase diagram in the detuning-pump coordinates, where the detuning is measured with respect to half the pump frequency. Near the boundary of the parametric phase transition the system becomes sensitive to external perturbations [1]. We show experimentally that this can be used as a threshold detector of single microwave photons, with efficiency of 73% [2]. We also demonstrate that some features of the Poissonian statistics are observable [3]. Finally, I will present a theoretical model that support these findings as well as numerical simulations of the corresponding Heisenberg-Langevin and Fokker-Planck equations.

References

[1] Roberto Di Candia, Fabrizio Minganti, KV Petrovnin, Gheorghe S Paraoanu, Simone Felicetti, Critical parametric quantum sensing, npj Quantum Information **9**, 23 (2023).

[2] K Petrovnin, J Wang, M Perelshtein, P Hakonen, GS Paraoanu, Microwave photon detection at parametric criticality, PRX Quantum **5**, 020342 (2024).

[3] J Wang, K Petrovnin, PJ Hakonen, GS Paraoanu, Observing the Poisson distribution of a coherent microwave field with a parametric photon detector, IEEE Transactions on Quantum Engineering **6**, 3500208 (2025).

Enhanced quantum frequency estimation by nonlinear scrambling

Matteo G. A. Paris, Victor Montenegro, Sara Dornetti, Alessandro Ferraro
University of Milan, Italy and IFFS - UESTC, Chengdu, China

Frequency estimation, a cornerstone of basic and applied sciences, has been significantly enhanced by quantum sensing strategies. Despite breakthroughs in quantum-enhanced frequency estimation, key challenges remain: static probes limit flexibility, and the interplay between resource efficiency, sensing precision, and potential enhancements from nonlinear probes remains not fully understood. In this work, we show that dynamically encoding an unknown frequency in a nonlinear quantum electromagnetic field can significantly improve frequency estimation. To provide a fair comparison of resources, we define the energy cost as the figure of merit for our sensing strategy. We further show that specific higher-order nonlinear processes lead to nonlinear-enhanced frequency estimation. This enhancement results from quantum scrambling, where local quantum information spreads across a larger portion of the Hilbert space. We quantify this effect using the Wigner-Yanase skew information, which measures the degree of noncommutativity in the Hamiltonian structure. Our work sheds light on the connection between Wigner-Yanase skew information and quantum sensing, providing a direct method to optimize nonlinear quantum probes.

References

[1] V. Montenegro, S. Dornetti, A. Ferraro, M. G. A. Paris, Enhanced quantum frequency estimation by nonlinear scrambling. preprint ArXiv:2503.01959

Quantum Metrology with Rydberg Atoms

M. Parniak[1,2]

[1] *Centre for Quantum Optical Technologies, Centre of New Technologies, University of Warsaw, S. Banacha 2c, 02-097 Warsaw Poland*
[2] *Faculty of Physics, University of Warsaw, L. Pasteura 5, 02-093 Warsaw, Poland*

The excellent sensitivity of Rydberg atoms to external electric fields is both their curse and one of the strongest feats. In our lab we exploit this feature to engineer very sensitive microwave sensors and microwave-optical transducers. However, simple scheme do not take any advantage of Rydberg-Rydberg interaction. Now we would like to present a sensing scheme, in which interactions are used to prepare the atomic state in such a way that the retrieved quantum state of light is less susceptible to inherent losses in the setup. The scheme utilized long-range dipolar interactions, and surprisingly allows for a very significant interaction even though the atomic ensemble is large and somewhat dilute. We cast our protocol in a quantum-metrological framework, and demonstrate that it is in fact an optimal solution to the given quantum error-correction problem. In the experiment, we show that interaction allow us to achieve a threefold enhancement in the Fisher information per detected photon. With future enhancements we project that the sensor will reach a sensitivity at the level of single microwave or mm-wave photons.

I will cast those results in the broader context of Rydberg-atom metrology, which ranges from cold-atom quantum memories [1] to sensing with hot-vapor cells [2].

References

[1] S. Kurzyna, B. Niewelt, M. Mazelanik, W. Wasilewski, and M. Parniak, Quantum 8, 1431 (2024)

[2] S. Borówka, U. Pylypenko, M. Mazelanik, and M. Parniak, Nature Photonics 18, 32 (2024)

Quantum Mechanics in a Quantum Reference Frame

Eugene S. Polzik

Niels Bohr Institute, Copenhagen University

A question of the limits of the measurement precision has always been one of the central topics in quantum mechanics. A special case based on the measurement relative to a quantum reference frame has been introduced and explored [1]. It has been shown that in a suitable reference frame the accuracy of measurements of spin projections and mechanical motion are not limited by the uncertainty principle. The development of this field dubbed “measurements in the negative mass reference frame” or “quantum mechanics free subspaces” has led to several applications. In the talk I will introduce the concept of a reference frame with an effective negative mass or frequency which forms the basis for such measurements. Experiments where a macroscopic object and a reference frame are driven deep into entangled quantum regime will be reviewed, including observation of a trajectory of motion in a quantum reference frame with, in principle, unlimited accuracy [2] and applications of those ideas to magnetometry [3] and gravitational wave detection [4, 5].

1. Nature, 413, 400 (2001); Nature, 547, 191 (2017).
2. Nature Physics (2020) 10.1038/s41567-020-1031-5.
3. Phys. Rev. Lett., 104, 133601 (2010).
4. Phys. Rev. Lett. 121, 031101 (2018)
5. arXiv:2412.11824, to appear in Nature (2025).

Manipulating Light with Bound States in the Continuum

Grazia Salerno[1,2]

[1] *Department of Applied Physics, Aalto University School of Science, Aalto FI-00076, Finland*
[2] *Dipartimento di Fisica, Università di Pisa, Largo Bruno Pontecorvo 3, Pisa, 56127, Italy*

The control of protected topological modes offers a promising route for quantum devices resilient to environmental perturbations. In photonic lattices, bound states in the continuum (BICs) appear as polarization vortices with nontrivial topological charge, exhibiting extremely high Q factors and minimal radiation loss. We demonstrate that plasmonic nanoparticle arrays can support lasing emission with polarization properties directly linked to BICs [1,2]. Furthermore, we investigate the interplay between symmetry and vortex rotationality, experimentally realizing lasing with topological charges as high as -5, +7, -17, and +19 [3]. The ability to generate and control such high-charge vortices suggests a potential route for encoding information in structured light. To further understand the topological properties of these modes, we introduce an effective non-Hermitian model to analyze the radiation Berry curvature, defined from the far-field polarization of outward-propagating waves, and compare it with the conventional bulk Berry curvature of Bloch modes [4]. Our results provide new insights into the geometric and topological control of light in open photonic systems with BICs, paving the way for novel applications in topological photonic devices and quantum technologies.

References

[1] R. Heilmann, G. Salerno, J. Cuerda, T.K. Hakala, and P. Törmä, *ACS Photonics* **9**, 224 (2022).

[2] G. Salerno, R. Heilmann, K. Arjas, K. Aronen, J.P. Martikainen, and P. Törmä, *Phys. Rev. Lett.* **129**, 173901 (2022).

[3] K. Arjas, J.M. Taskinen, R. Heilmann, G. Salerno and P. Törmä, *Nat. Commun.* **15**, 9544 (2024).

[4] X. Yuan, L. Malgrey, H. Sigurðsson, H.S. Nguyen and G. Salerno, *arXiv*:2504.05188 (2025).

Light interactions with polar quantum systems

P. Gładysz[1], N. Petkova[2], G. Scala[3], P. Wcisło[1], P. Facchi[4], S. Pascazio[4], F. Pepe[4], K. Słowik*[1]

[1] *Institute of Physics, Nicolaus Copernicus University in Toruń, Grudziądzka 5/7, 87-100 Toruń, Poland*
[2] *University of St Andrews, School of Physics and Astronomy, St Andrews, UK*
[3] *Politecnico di Bari, I-70126 Bari, Italy*
[4] *Dipartimento Interateneo di Fisica, Universit`a degli Studi di Bari, I-70126 Bari, Italy and INFN, Sezione di Bari, I-70125 Bari, Italy*

The optical properties of atomic systems are shaped by their spatial symmetries, which are captured through multipolar transition moments. These values are tied to selection rules that determine which transitions can take place in a quantum system. In contrast, permanent multipolar moments are often brushed aside, assumed to cause only trivial energy shifts. This work explores light–matter interaction regimes where that assumption no longer holds.

A paradigmatic quantum effect altered in polar systems is the familiar Rabi population transfer. When it takes place between eigenstates that carry permanent dipole moments, it leads to an additional oscillating dipole—one that radiates at the Rabi frequency [1,2]. Interestingly, this frequency can be controlled across a broad spectral range, which opens the door to all-optically tunable sources of coherent radiation [3,4].

Permanent dipole moments also change how light couples to matter. In non-polar systems, the interaction strength grows linearly with the amplitude of the electric field. But in polar systems under strong fields, this scaling can shift—pointing to a new regime of coherent dynamics, potentially resilient even in the presence of strong spatial variations in the driving field [5-7].

References

[1] O. V. Kibis, G. Slepyan, S. A. Maksimenko, A. Hoffmann, Phys. Rev. Lett. 102, 023601 (2009).

[2] G. Scala, K. Słowik, P. Facchi, S. Pascazio, F. V. Pepe, Phys. Rev. A 104, 013722 (2021).

[3] I. Chestnov, V. A. Shahnazaryan, A. P. Alodjants, I. A. Shelykh, ACS Photonics 4, 2726-2737 (2017).

[4] P. Gładysz, P. Wcisło, K. Słowik, Sci. Rep. 10, 17615 (2020).

[5] P. Gładysz, K. Słowik, Phys. Rev. A 11 (5), 053704 (2025).

[6] F. Pepe, K. Słowik, Phys. Rev. Lett. 133 (8), 083603 (2024).

[7] N. Petkova, P. Gładysz, K. Słowik, in preparation

Multiparameter quantum metrology with an array of entangled atomic sensors

Yifan Li[1], Lex Joosten[1], Paolo Colciaghi[1], Michał Lipka[1], Youcef Baamara[2], Alice Sinatra[2], Tilman Zibold[1], and Philipp Treutlein[1]

[1]*University of Basel, Department of Physics, Klingelbergstrasse 82, 4056 Basel, Switzerland*
[2]*Laboratoire Kastler Brossel, ENS-Université PSL, CNRS, Université de la Sorbonne and Collège de France, 24 rue Lhomond, 75231 Paris, France*

In quantum metrology, entangled states of many-particle systems are investigated to enhance measurement precision of the most precise clocks and field sensors. While single-parameter quantum metrology is well established, many metrological tasks require joint multiparameter estimation, which poses new conceptual challenges that have so far only been explored theoretically.

We experimentally demonstrate multiparameter quantum metrology with an array of entangled atomic ensembles [1]. By splitting a spin-squeezed Bose-Einstein condensate, we create an atomic sensor array featuring inter-sensor entanglement of the Einstein-Podolsky-Rosen type [2]. Local spin rotations applied to the individual sensors allow us to flexibly configure the entanglement to enhance measurement precision of multiple parameters jointly [3]. Using an optimal estimation protocol, we achieve significant gains over the standard quantum limit in key multiparameter estimation tasks of relevance for field sensor arrays and imaging devices.

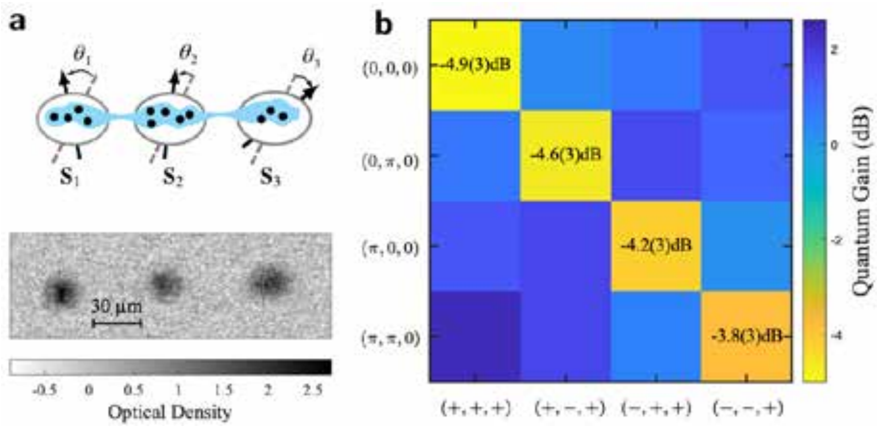


Figure: Joint multiparameter estimation with three entangled atomic sensors. (a) Schematic of the three entangled sensor spins on which three local parameters are imprinted (top) and absorption image of the three atomic clouds (bottom). (b) Matrix of metrological gains compared to the standard quantum limit for different sensor preparations and estimated parameter combinations.

References

[1] Y. Li, L. Joosten, Y. Baamara, P. Colciaghi, A. Sinatra, P. Treutlein, and T. Zibold, *Multiparameter estimation with an array of entangled atomic sensors*, preprint arXiv:2504.08677 (2025).

[2] P. Colciaghi, Y. Li, P. Treutlein, and T. Zibold, *Einstein-Podolsky-Rosen experiment with two Bose-Einstein condensates*, Phys. Rev. X 13, 021031 (2023).

[3] Y. Baamara, M. Gessner, and A. Sinatra, *Quantum-enhanced multiparameter estimation and compressed sensing of a field*, SciPost Phys. 14, 050 (2023).

Testing the Interplay Between Gravity and Quantum Mechanics with Optomechanical Systems

David Vitali[1,2,3],

[1] *Physics Division, School of Science and Technology, University of Camerino, Camerino, Italy*
[2] *INFN, Sezione di Perugia, Perugia, Italy*
[3] *CNR-INO Firenze, Italy*

Optomechanical devices operated in the quantum regime represent a promising platform for testing foundations of physics. In fact, they allow extreme sensitivity for force and displacement sensing, ranging from gravitational wave detectors to interferometers with massive trapped particles, or actuated nanomembranes. We shall describe two different classes of experiments aiming at bridging the gap between quantum theory and gravity. A first proposal applies results from Quantum Communication theory and exploits a criterion providing a sufficient condition for proving the necessity of quantizing the gravity field in a model-independent way, that is, without any assumption on the gravitational interaction [**1**]. Assuming also a linearized treatment of the Newtonian interaction between the two mechanical resonators of two face-to-face optomechanical cavity systems, one can perform a quantitative analysis able to determine the most convenient parameter regime for designing the experiment.

In a second proposal we consider the generation of large amplitude coherent states as practically optimal probes for measuring weak nonlinearities, which may emerge either from material properties of the resonator, of from the nonrelativistic limit of deformed commutator theories of quantum gravity [**2**].

References

[1] A. Mari, S. Zippilli, D. Vitali, arXiv:2504.05998 [quant-ph].

[2] W. Li *et al.,* arXiv:2504.07486 [quant-ph].

Quantum Control for Quantum Computation, Sensing and Imaging

Nikolay V. Vitanov

Center for Quantum Technologies, Faculty of Physics, Sofia University, Bulgaria

In this talk recent results from quantum control experiments with trapped ions, doped solids, and superconducting qubits are reported. They include demonstration of broadband composite pulses – trains of pulses with well-defined relative phases – for complete (X gates) and partial (Hadamard and general rotation gates), which cancel the experimental errors to an arbitrary order [1-3]. Alternatively, narrowband composite pulses which squeeze excitation to an arbitrarily narrow parameter range, are used for spatial localization in doped solids and accurate phonon counting in trapped ions [3-6]. The composite idea is extended to new, very efficient dynamical decoupling sequences [7,8]. Another example is the newly proposed quantum control technique of polychromatic pulse trains – sequences of pulses of appropriately chosen different frequencies [9]. In another set of experiments, we have observed the counterintuitive phenomenon of power narrowing with driving pulses of Lorentzian shape – the squeezing of the excitation line profile when the Rabi frequency increases – by as much as a factor of 10 [10], potentially enabling new quantum sensing tools.

References

[1] J. Randall, A. M. Lawrence, S. C. Webster, S. Weidt, N. V. Vitanov, and W. K. Hensinger, *Generation of high-fidelity quantum control methods for multi-level systems*, Phys. Rev. A **98**, 043414 (2018).

[2] M. Duwe, G. Zarantonello, N. Pulido-Mateo, H. Mendpara, L. Krinner, A. Bautista-Salvador, N. V. Vitanov, K. Hammerer, R. F. Werner, C. Ospelkaus, *Numerical optimization of amplitude-modulated pulses in microwave-driven entanglement generation*, Quantum Sci. Tech **7**, 045005 (2022).

[3] B.T. Torosov and N.V. Vitanov, *Experimental demonstration of composite pulses on IBM's quantum computer*, Phys. Rev. Appl. **18**, 034062 (2022).

[4] B.T. Torosov and N.V. Vitanov, *Narrowband composite two-qubit gates for crosstalk suppression*, Phys. Rev. A **107**, 032618 (2023).

[5] Markus Stabel, Niels Joseph, Nikolay V. Vitanov, and Thomas Halfmann, *Spatial confinement of atomic excitation by composite pulses in a doped solid*, Phys. Rev. A **110**, 023526 (2024).

[6] Marion Mallweger, Milena Guevara-Bertsch, Boyan T. Torosov, Robin Thomm, Natalia Kuk, Harry Parke, Christan F. Roos, Gerard Higgins, Markus Hennrich, and Nikolay V. Vitanov, *Motional-state analysis of a trapped ion by ultranarrowband composite pulses*, Phys. Rev. A **110**, 053103 (2024).

[7] G. T. Genov, D. Schraft, N. V. Vitanov, and T. Halfmann, *Arbitrarily accurate pulse sequences for robust dynamical* decoupling, Phys. Rev. Lett. **118**, 133202 (2017).

[8] Xinxing Yuan, Yue Li, Mengxiang Zhang, Chang Liu, Mingdong Zhu, Xi Qin, Nikolay V. Vitanov, Yiheng Lin, and Jiangfeng Du, *Preserving multi-level quantum coherence by dynamical decoupling*, Phys. Rev. A **106**, 022412 (2022).

[9] S.S. Ivanov, B.T. Torosov and N.V. Vitanov, *High-fidelity quantum control by polychromatic pulse trains*, Phys. Rev. Lett. **129**, 240505 (2022).

[10] I.S. Mihov and N. V. Vitanov, *Defying Conventional Wisdom in Spectroscopy: Power Narrowing on IBM Quantum*, Phys. Rev. Lett. **108**, 020802 (2024).

Exploiting Quantum Photonics for Quantum Machine Learning

Philip Walther[1,2]

[1] *University of Vienna, Faculty of Physics, Vienna Center for Quantum Science and Technology (VCQ), Boltzmanngasse 5, 1090 Vienna, Austria*
[2] *Institute for Quantum Optics and Quantum Information (IQOQI) Vienna, Austrian Academy of Sciences, Boltzmanngasse 3, Vienna, Austria*

After providing a brief overview of recent advancements in the generation and processing of multi-photon states [1], I will show the potential of photonic quantum machine learning. After presenting a quantum-enhanced reinforcement learning using a tunable integrated processor [2], I will discuss our development of a so-called quantum memristor for single photons [3]. These devices, which can mimic the behavior of neurons and synapses, hold great promise for the realization of quantum neural networks. I will also present how photonic processors can implementing quantum-enhanced kernels for machine learning tasks [4]. At the end I will change topic by briefly discussing the flexibility of photonic systems for tasks that require non-standard quantum computer architectures [5].

References

[1] L. Carosini, V. Oddi, F. Giorgino, L. M. Hansen, S. Piacentini, T. Guggemos, I. Agresti, J. C. Loredo, P. Walther, Science Advances 10, eadj0993 (2024).

[2] V. Saggio, B.E. Asenbeck, A. Hamann, T. Strömberg, P. Schiansky, V. Dunjko, N. Friis, N.C. Harris, M. Hochberg, D. Englund, S. Wölk, H. J. Briegel, P. Walther, Nature 591, 229 (2021).

[3] M. Spagnolo, J. Morris, S. Piacentini, M. Antesberger, F. Massa, A. Crespi, F. Ceccarelli, R. Osellame, P. Walther, Nature Photonics 16, 318 (2022).

[4] Z. Yin, I. Agresti, G. de Felice, D. Brown, A. Toumi, C. Pentangelo, S. Piacentini, A. Crespi, F. Ceccarelli, R. Osellame, B. Coecke, P. Walther, Nature Photonics (2025).

[5] P. Schiansky, T. Strömberg, B. Trillo, V. Saggio, B. Dive, M. Navascués, P. Walther, Optica 10, 200 (2023).

Engineering Unitary and Dissipative Dynamics for Quantum Applications

Chiao-Hsuan Wang[1,2,3]

[1] *Department of Physics, National Taiwan University, Taipei 106319, Taiwan*
[2] *Center for Quantum Science and Engineering, National Taiwan University, Taipei 106319, Taiwan*
[3] *Physics Division, National Center for Theoretical Sciences, Taipei 106319, Taiwan*

Tailored unitary interactions and engineered dissipation provide powerful tools for advancing quantum applications. In this talk, I will present two complementary techniques that leverage these capabilities to enhance quantum control, coherence, and computation.

The first technique focuses on squeezed thermal reservoir engineering [1]. By coupling a target quantum system to a lossy mode within a normal thermal environment, we emulate a squeezed reservoir with distinct, tunable fluctuations along phase-space quadratures. We demonstrate the creation of a squeezed thermal reservoir for both two-level systems and bosonic modes, enabling applications in dissipative squeezing, entanglement stabilization, quantum simulations, and quantum thermodynamics.

The second technique introduces an analog approach to quantum phase estimation based on continuous dynamics, which avoids common errors in digital quantum computation and may be well-suited for near-term quantum devices [2]. This method offers a scalable and hardware-efficient path for solving eigenvalue problems in quantum many-body systems, with circuit quantum electrodynamics (cQED) as a promising platform for realization.

References

[1] C.-L. Lee and C.-H. Wang, arXiv:2408.16052 (2024).

[2] W.-C. Lin and C.-H. Wang, arXiv:2506.15668 (2025).

HOT TOPICS

A tensor network approach to sensing quantum light-matter interactions

A. Khan[1,2], F. Albarelli[3], and A. Datta[4]

[1] *Department of Physics and Astronomy, University of Exeter, Exeter EX44QL, United Kingdom*
[2] *School of Mathematics and Physics, University of Portsmouth, Portsmouth PO12UP, United Kingdom*
[3] *Scuola Normale Superiore, I-56126 Pisa, Italy*
[4] *Department of Physics, University of Warwick, Coventry CV47AL, United Kingdom.*

We present the fundamental limits to the precision of estimating parameters of a quantum matter system probed by light, even when some of the light is lost. This practically inevitable scenario leads to a tripartite system of matter and light—detected and lost, where evaluating fundamental information theoretic quantities such as the quantum Fisher information were heretofore impossible, and limited to the bipartite case without losses [1]. We succeed by expressing the final quantum state of the detected light as a matrix product operator, leveraging a variational technique to evaluate the QFI for such states [2]. We apply our method to resonance fluorescence and pulsed spectroscopy. For both, we quantify the sub-optimality of continuous homodyning and photo-counting measurements in parameter estimation [3, 4]. For the latter, we find that single-photon Fock state pulses allow higher precision per photon than pulses of coherent states [5]. Our method should be valuable in the study of quantum light-matter interactions, quantum light spectroscopy, quantum stochastic thermodynamics, and quantum clocks [6].

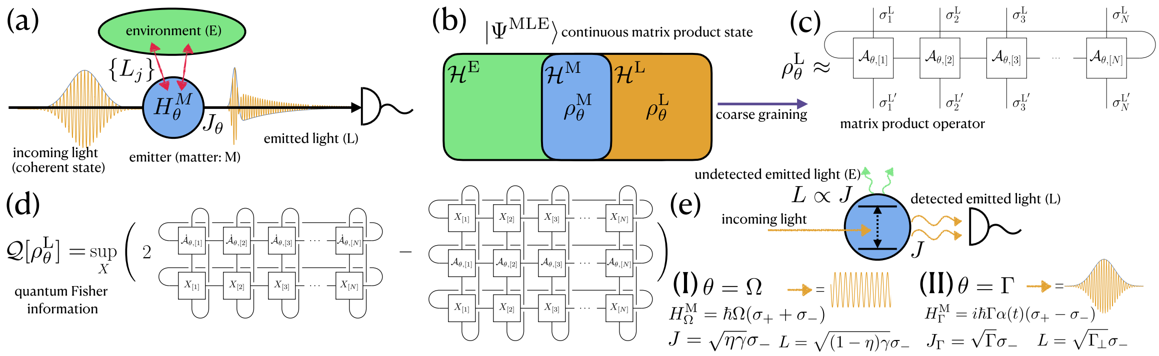


Figure 1: (a) Schematic representation of our tripartite setup. The emitter (M), a matter system with Hamiltonian H_θ^{M}, interacts with propagating light (L), initially in a coherent state, through an operator J_θ, and also with the environment (E), resulting in the Lindblad operators L_j acting on M. Only L can be detected after the interaction. (b) Tripartism: The tripartite Hilbert space structure $\mathcal{H}^{\mathrm{M}} \otimes \mathcal{H}^{\mathrm{L}} \otimes \mathcal{H}^{\mathrm{E}}$. The evolution caused by E is purified to an Hamiltonian interaction with operators L_j. The tripartite state $|\Psi^{\mathrm{MLE}}\rangle$ is a pure continuous matrix product state. (c) After coarse-graining into time-bins of size Δt, the reduced state of the light ρ_θ^{L} is approximately described by a matrix product operator. (d) The QFI of a state in MPO form is computed variationally [2] (e) Two case studies considered in this work: (I) Rabi frequency Ω estimation in resonance fluorescence with detectors of efficiency $\eta < 1$; and (II) dipole-moment Γ estimation of a two-level system with pulsed classical light, when not all emitted light can be detected. $\Gamma_\perp$ denotes emission into inaccessible modes.

References

[1] D. Yang, S. F. Huelga, and M. B. Plenio, Phys. Rev. X 13, 031012 (2023).

[2] K. Chabuda, J. Dziarmaga, T. J. Osborne, and R. Demkowicz-Dobrzański, Nat. Commun. **11**, 250 (2020).

[3] A. H. Kiilerich and K. Mølmer, Phys. Rev. A 89, 052110 (2014).

[4] A. H. Kiilerich and K. Mølmer, Phys. Rev. A 94, 032103 (2016).

[5] F. Albarelli, E. Bisketzi, A. Khan, and A. Datta, Phys. Rev. A 107, 062601 (2023).

[6] V. Singh, E. Kwon, and G. J. Milburn, arXiv:2503.12118 (2025).

Distinguishability tomography of multiple interfering photons

E. Annoni[1,2], S.C. Wein[2]

[1] *Centre for Nanosciences and Nanotechnology, Université Paris-Saclay, UMR 9001,10 Boulevard Thomas Gobert, 91120, Palaiseau, France*
[2] *Quandela SAS, 7 Rue Léonard de Vinci, 91300 Massy, France*

The growing interest in using single photons for quantum communication, metrology and quantum information processing introduced the need to understand and characterize how sensitive interference protocols are to realistic imperfections [1]. In this context, photon distinguishability plays a key role in quantifying the quality of interference, a first-order requirement to exploit the non-classical properties of the photons. The routine visibility measurement of the Hong-Ou-Mandel (HOM) dip provides an estimate of the distinguishability via a wavefunction overlap between two distinct photons; nevertheless, this pairwise information turns out to be insufficient to explain the genuine many-body effects that can impact a multi-photon interference experiment, the simplest example being the triad phase [2]. Earlier works showed that, in order to capture the interference behavior of n arbitrary, mixed and possibly entangled single-photon states, one must either resort to a group-theoretic decomposition into irreducible representations or use up to $n!$ independent complex-valued parameters [3].

In our work [4] we further develop the latter approach, proving how this finite set of quantities (the average value of the mode permutation operators $\langle \hat{P}_\sigma \rangle$, cfr. Fig.1) constitutes a non-redundant quorum of observables that captures the interference properties of an n-photon state that are relevant to linear optics and photocounting. We further show how these quantities can be unambiguously measured with a family of interferometers. These two key facts lead to a clear definition of what a complete "distinguishability tomography" is for multi-photon states, providing a novel tool to assess the quality of photon interference experiments. Furthermore, we discuss how the results of this tomography can be employed to distinguish between "coherent" and "incoherent" distinguishability noise, providing valuable information needed to design effective photonic error mitigation and distillation schemes. We finally implement the "distinguishability tomography" procedure on a reconfigurable chip [5], probing the distinguishability spectrum of the 4 photon state produced from a time-demultiplexed Quantum Dot single-photon source.

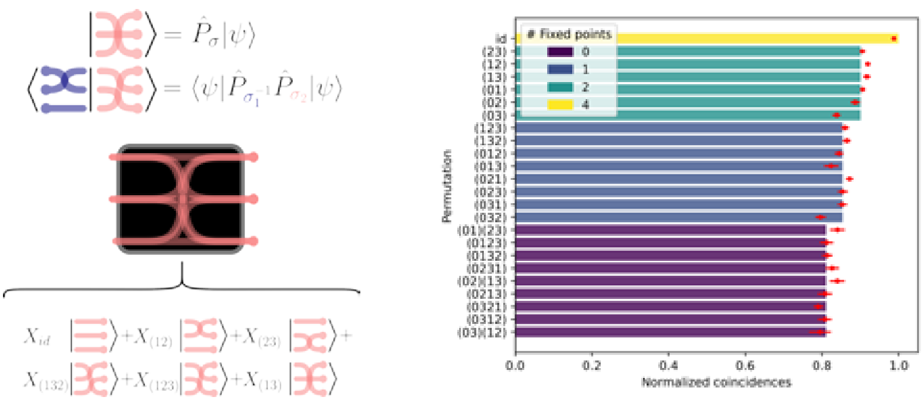


Figure 1: **left)** Depiction of the path based decomposition of multi-photon interference [3]. The probability to observe a given outcome can be shown to depend on the $n!$ observables $\hat{P}_\sigma$, which generalize pairwise HOM distinguishability **right)** Results of the 4-photon distinguishability tomography showing the measured value of $\langle \hat{P}_\sigma \rangle$ compared with a model assuming uniform pairwise HOM.

References

[1] I. Walmsley, Optica Quantum **1**, 35 (2023).

[2] A. J. Menssen et al., Physical Review Letters **118**, 153603 (2017).

[3] V. S. Shchesnovich, Physical Review A **91**, 013844 (2015).

[4] E. Annoni and S. C. Wein, *Incoherent behavior of partially distinguishable photons*, (Feb. 7, 2025) `http://arxiv.org/abs/2502.05047`.

[5] N. Maring et al., Nature Photonics, `10.1038/s41566-024-01403-4` (2024).

Noise correlation measurements as a probe of spontaneously symmetry-broken phases in cold atoms

J. Argüello-Luengo[1]

[1] *Departament de Física, Universitat Politécnica de Catalunya, Campus Nord B4-B5, 08034 Barcelona, Spain*

Spontaneously symmetry-broken (SSB) phases are locally ordered states of matter characterizing a large variety of physical systems [1]. Because of their specific ordering, their presence is usually witnessed by means of local order parameters. However, diffraction limit poses a challenge to this single-site imaging of dipolar atoms in subwavelength lattices [2]. As an alternative, here we propose an approach based on statistical correlations of noise after the ballistic expansion of an atomic cloud [3,4]. We indeed demonstrate that probing such noise correlators allows one to discriminate among different SSB phases characterized by spin-charge separation. As a particular example, we test our prediction on a 1D extended Fermi-Hubbard model, where the competition between local and nonlocal couplings gives rise to three different SSB phases: a charge density wave, a bond-ordering wave, and an antiferromagnet (see Fig. 1). Our numerical analysis shows that this approach can accurately capture the presence of these different SSB phases, thus representing an alternative and powerful strategy to characterize strongly interacting quantum matter [5].

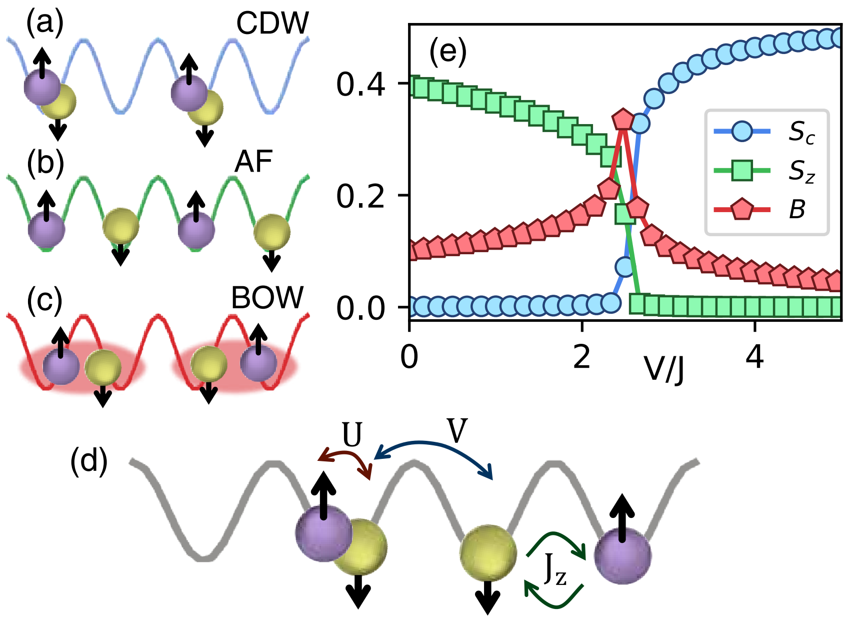


FIG. 1: Illustration of the charge-density wave (CDW) (a), antiferromagnet (AF) (b), and bond-order wave (BOW) (c) phases. (d) Schematic representation of the 1D extended Fermi-Hubbard (EFH) model at half occupation studied in this work. Atoms of different spin are illustrated with different colors and two-point arrows indicate on-site (U) and nearest-neighbor (V) interactions. An additional term (J_z) couples the spin of neighbor sites. (e) Phase diagram associated to the ground-state of the EFH. As the value of V/J increases, one observes the transition between the previous three spontaneously symmetry-broken phases [5].

References

[1] N. Baldelli, A, Montorsi,S, Julià-Farré, M. Lewenstein, M. Rizzi, L. Barbiero, arXiv:2407.04073 (2024)
[2] L. Su, et al., Nature 622, 724 (2023).
[3] E. Altman, E. Demler, and M. D. Lukin, Phys. Rev. A 70, 013603 (2004).
[4] I. B. Spielman, W. D. Phillips, and J. V. Porto, Phys. Rev.Lett. 98, 080404 (2007).
[5] K. Gallego-Lizarribar, S. Julià-Farré, M. Lewenstein, C. Weitenberg, L. Barbiero, J. Argüello-Luengo, Phys. Rev. Research 6, L042048 (2024)

Memory-Dependent Quantum Transformations with a Photonic Quantum Memristor

Karol Bartkiewicz, Patrycja Tulewicz, Adam Miranowicz

Institute of Spintronics and Quantum Information, Adam Mickiewicz University, PL-61-614 Poznań, Poland

We present a theoretical proposal for a quantum memristor operating at the single-photon level, implementing memristive behavior, including characteristic hysteresis loops, in a quantum optical system through measurement-based feedback on photonic polarization states [**1**]. Analogous to classical memristors where resistance depends on the system's past electrical history, our quantum device transforms input photon states according to $|\psi_{\text{out}}(t)\rangle = \hat{U}(\theta(t))\,|\psi_{\text{in}}(t)\rangle$, where the unitary operator $\hat{U}(\theta)$ evolves based on measurement outcomes of previous photons, exhibiting path-dependent memory effects [**2**]. Unlike classical memristors that rely on material properties, our theoretical device achieves memory effects through quantum measurements and high-speed feedback, with dynamics characterized by $\frac{d\theta}{dt} = \eta N(t) + \gamma(\theta_0 - \theta)$, where η is the feedback strength, $N(t)$ represents detection events, and γ is the relaxation rate. The theoretical model predicts high state fidelity while operating under timing constraints where feedback processes must complete within the photon coherence time (∼µs). Our proposal provides insights into implementing quantum memristive systems in an alternative way to [**3**] and provides a framework that could potentially offer advantages in terms of operational fidelity and coherence time constraints with applications in photonic quantum computing, adaptive quantum sensing, and neuromorphic quantum architectures.

References

[1] K. Lemr et. al., Experimental Implementation of Optimal Linear-Optical Controlled-Unitary Gates, Phys. Rev. Lett., 114, 153602, (2015).

[2] J. Salmilehto et al., Quantum memristors with superconducting circuits, Sci. Rep. **7**, 42044 (2017).

[3] M. Spagnolo et al., Experimental photonic quantum memristor, Nature Physics **18**, 1056 (2022).

Towards generating a GKP Bell state by entangling two qunaught states with a beamsplitter

F. Berterottière[1-2], **J. Metzner**[1-2], **M. Fontboté-Schmidt**[1-2], **S. Welte**[3], **M. Wagener**[1-2], **D. Kienzler**[1-2], **J. Home**[1-2]

[1] *Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland*
[2] *Quantum Center, ETH Zürich, 8093 Zürich, Switzerland*
[3] *University of Stuttgart, Keplerstraße 7, 70174 Stuttgart, Germany*

Gottesman-Kitaev-Preskill (GKP) states[1], or grid states, encode logical qubits in quantum harmonic oscillators. Motional modes of a trapped ion are naturally accessible harmonic oscillators with coherence times of tens of milliseconds. They can be controlled by their coupling to the electronic degree of freedom of the ion, enabling the preparation[2] and readout[3] of GKP states using conditional displacements.

Generalized grid states[4] (qunaught states), encoding no logical information, can provide a source for GKP logical Bell states when entangled using a beamsplitter interaction[5]. We experimentally prepare either GKP states (Fig. 1) or qunaught states in two motional modes of a single trapped ion. We produce a beamsplitter interaction[6-7] by modulation of the harmonic potential, and demonstrate arbitrary swapping of single phonon states (Fig. 2). This work showcases the necessary components for generating a GKP Bell state by entangling two qunaught states.

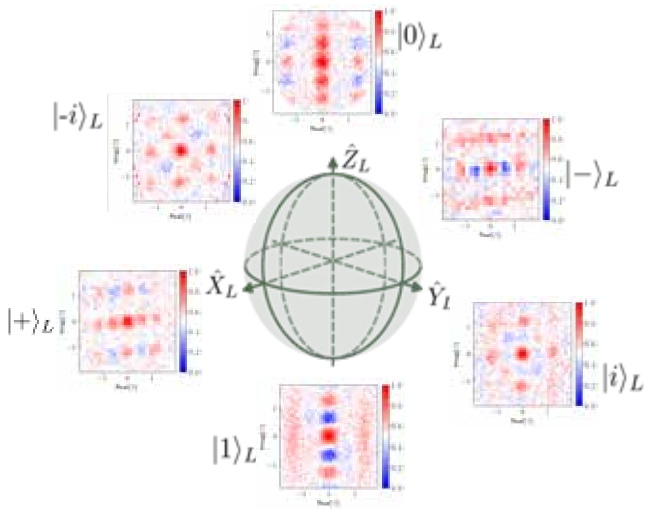


FIG. 1: Experimental preparation of logical GKP states at the cardinal points of the Bloch sphere. The states are read out by characteristic function tomography[3].

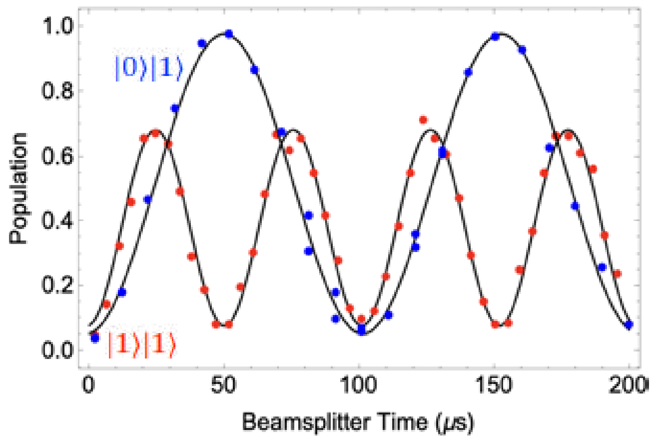


FIG. 2: Swap of a single phonon (blue) and Hong-Ou-Mandel interference (red) between the two motional modes via the beamsplitter[6-7].

References

[1]D. Gottesman, A. Kitaev, J. Preskill, Phys. Rev. A **64**, 012310 (2001).

[2] C. Flühmann *et al.,* Nature **566**, 513–517 (2019).

[3] C. Flühmann, J. P. Home., Phys. Rev. Lett. **125**, 043602 (2020).

[4] K. Duivenvoorden, *et al.* Phys. Rev. A **95**, 012305 (2017).

[5] B.W. Walshe, *et al*., Phys. Rev. A **102**, 062411 (2020).

[6] K. R. Brown, et al., Nature **471**, 196 (2011).

[7] P.-Y. Hou, *et al*., Nat. Phys. **20**, 1636–1641 (2024).

All-fiber microendoscopic polarization sensing at single-photon level aided by deep-learning

Martin Bielak[1], Dominik Vašinka[1], and Miroslav Ježek[1]

[1] *Department of Optics, Faculty of Science, Palacky University, 17. listopadu 12, 77900 Olomouc, Czech Republic*
*bielak@optics.upol.cz

Light polarization plays a fundamental role across various scientific disciplines, from ellipsometry and optical communications to microscopy and sensing. Specifically, the polarization of light emitted by optically anisotropic specimens carries critical information about their material structure and optical properties. However, achieving precise polarization measurements under challenging conditions, such as constrained spaces, low light levels, and high-speed scenarios, remains a significant challenge.

To address this issue, we introduce a real-time polarization measurement method capable of achieving single-photon-level accuracy while providing complete information about the polarization state. Our polarization sensor, which is free of moving components and depicted in Fig. 1(a), utilizes a common few-mode fiber along with a fiber array and a detector array to characterize the input polarization state. This setup is augmented by a deep machine-learning model, reconstructing complete real-time polarization information. The calibrated sensor exhibits exceptional accuracy, achieving an unprecedented infidelity of 8×10^{-4}. This outstanding level of performance has remained remarkably stable for over a month, requiring no additional calibration or network retraining.

We demonstrate the capabilities of our approach through polarization-sensitive scans of an optically anisotropic specimen. The reconstructed polarization scan of a piece of dense connective tissue is visualized through false-colored RGB images (Fig. 1(b)), shown side by side with an intensity image of the same sample region. Additionally, we used the sensor to characterize the twisted nematic liquid crystal transition effect and to analyze the standardized USAF test target.

These demonstrations confirm our polarization sensor's suitability for diverse sensing applications and highlight its invaluable contributions to precise polarization measurements. This sensor opens new frontiers in precise polarization measurement, offering a powerful tool for advanced applications in biomedicine, material research, and beyond.

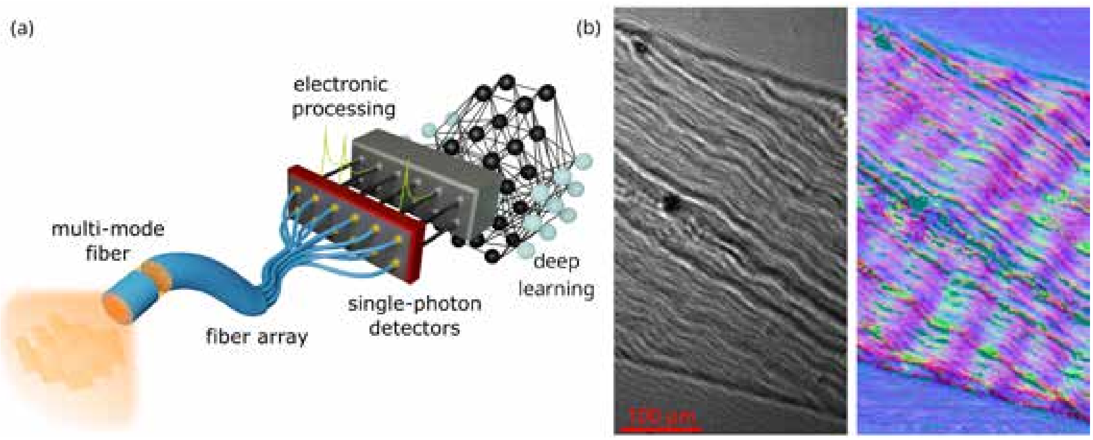


Figure 1: (a) A visual representation of the all-fiber polarization sensor. (b) Visualization of dense connective tissue: (left) intensity image and (right) a scan using the all-fiber polarization sensor. The resulting Bloch parameters are represented as an RGB false-colored image.

References

[1] Bielak, Martin, et al. "All-fiber microendoscopic polarization sensing at single-photon level aided by deep-learning." arXiv, 2024, doi:10.48550/arXiv.2405.02172.

H7

Two-dimensional sub-wavelength topological lattices for dark-state ultracold atoms

D. Burba[1], **G. Juzeliūnas**[1]

[1] *Institute of Theoretical Physics and Astronomy, Department of Physics, Vilnius University, Saulėtekio al. 3, LT-10257, Vilnius, Lithuania*

Ultracold atoms represent a flexible platform for simulating topological and many-body phenomena of condensed matter and high-energy physics. The use of atomic dark states (long-lived superpositions of atomic internal ground states immune to atom-light coupling) offers new possibilities for such simulations. Making the dark states position-dependent, one can generate a synthetic magnetic field for ultracold atoms adiabatically following the dark states [1]. Recently, two-dimensional (2D) dark-state lattices were considered [2,3].

Here we present a general description of 2D topological dark state lattices elucidating an interplay with the sub-wavelength lattices [4]. In particular, we demonstrate that one can create a 2D Kronig-Penney lattice representing a periodic set of 2D subwavelength potential peaks affected by a non-staggered magnetic flux. Away from these patches of the strong magnetic field, there is a smooth magnetic flux of the opposite sign, compensating for the former peaks. While the total magnetic flux is zero, the system supports topological phases due to the flux variation over a unit cell, akin to Haldane-type lattice models with zero net flux over an elementary cell, but non-trivial topology due to non-zero fluxes over the plaquettes constituting the elementary cell. This work paves the way for experimental exploration of topological phases in dark-state optical lattices, offering new possibilities for simulating quantum Hall systems, fractional Chern insulators and related strongly correlated phases.

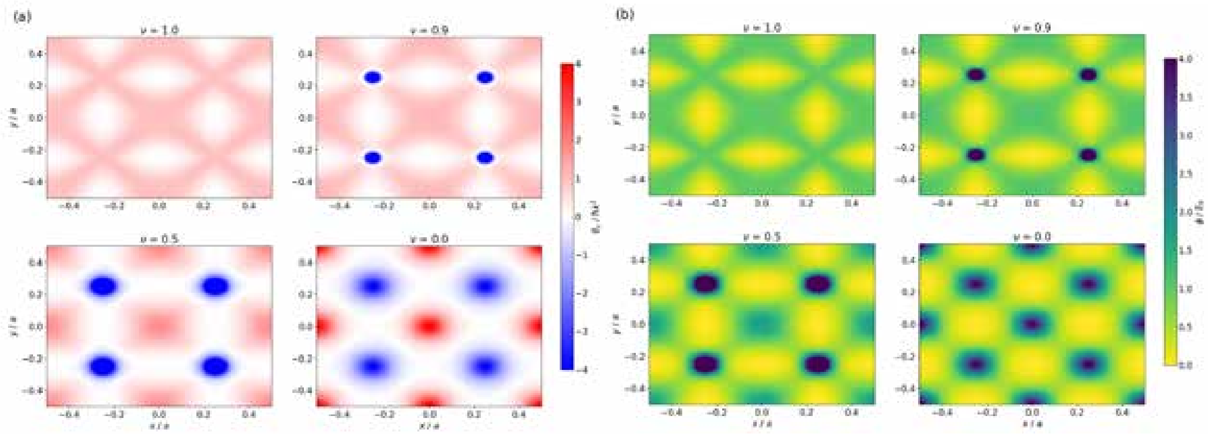


Figure 1: Spatial dependence of the **(a)** magnetic field B_z and **(b)** geometric potential ϕ for $\epsilon = 1$ and $\nu = \{1, 0.9, 0.5, 0\}$ when $\Delta = 2000E_\mathrm{R}$, $\Gamma = 1000E_\mathrm{R}$ and $\Omega_0 = 2000E_\mathrm{R}$. Note that the magnetic field and scalar potential around the narrow peaks are far beyond the range of their values shown. Specifically, the largest $|B_z|$ and ϕ are equal approximately to $\{1, 400, 16, 4\}\,\hbar k^2$ and $\{1, 400, 16, 4\}\,E_\mathrm{R}$ for $\nu = \{1, 0.9, 0.5, 0\}$, respectively.

References

[1] N. Goldman, G. Juzeliūnas, P. Öhberg, and I. B. Spielman, Rep. Prog. Phys., 77,126401 (2014).

[2] E. Gvozdiovas, I. B. Spielman, and G. Juzeliūnas, Phys. Rev.. A, 107, 033328 (2023).

[3] S. Nascimbene and J. Dalibard, arXiv:2412.15038 (2024).

[4] D. Burba and G. Juzeliūnas, arXiv:2506.17096 (2025).

Programmable quantum photonic circuit in free space

M. G. Ammendola[1,2], N. Dehghan[3,4], L. Scarfe[3], A. D'Errico[3,4], F. Di Colandrea[1,3], L. Marrucci[1], E. Karimi[3,4,5], **F. Cardano**[1]

[1] *Dipartimento di Fisica, Università degli Studi di Napoli Federico II, Via Cintia, 80126 Napoli, Italy*
[2] *Scuola Superiore Meridionale, Via Mezzocannone, 4, 80138 Napoli, Italy*
[3] *Nexus for Quantum Technologies, University of Ottawa, K1N 5N6, Ottawa, ON, Canada*
[4] *National Research Council of Canada, 100 Sussex Drive, Ottawa ON Canada, K1A 0R6*
[5] *Institute for Quantum Studies, Chapman University, Orange, California 92866, USA*

Photonic circuits engineered to couple optical modes according to a specific map act as processors for classical and quantum light. They enable tasks such as vector-matrix multiplications and unitary transformations, underpinning applications in quantum computing, optical simulations, and AI systems [1, 2].

We present a photonic platform implementing prototypical unitary evolutions known as quantum walks, using optical modes of the form $|m_x, m_y, j\rangle = A(x, y, z)\, e^{ik_z z} e^{i(m_x x + m_y y)\Delta k_\perp} |j\rangle$, where $A(x, y, z)$ is a Gaussian envelope with waist ω_0, k_z the longitudinal wavevector component, $\Delta k_\perp$ the transverse momentum unit, $m_{x,y} \in \mathbb{Z}$, and $|j\rangle = |L\rangle, |R\rangle$ circular polarization states. To suppress mode crosstalk, the condition $\omega_0 > 2\pi/\Delta k_\perp$ must be satisfied [3] (see Fig. 1(a)).

A recently demonstrated technique allows compressing arbitrarily complex evolutions into three static liquid crystal (LC) devices for both 1D and 2D quantum walks, greatly reducing optical losses [4, 5]. Building on these results, we demonstrate a programmable implementation of such a circuit, coupling transverse optical modes via three LC spatial light modulators (SLMs) and uniform waveplates. The correct transformation is implemented after carefully computing the phase patterns $(\delta_1, \delta_2, \delta_3)$, respectively.

The output intensity is collected in the focal plane of a lens, acting as a mode sorter. Figure 1(b) shows time-resolved distributions over 30 steps of a 1D quantum walk process.

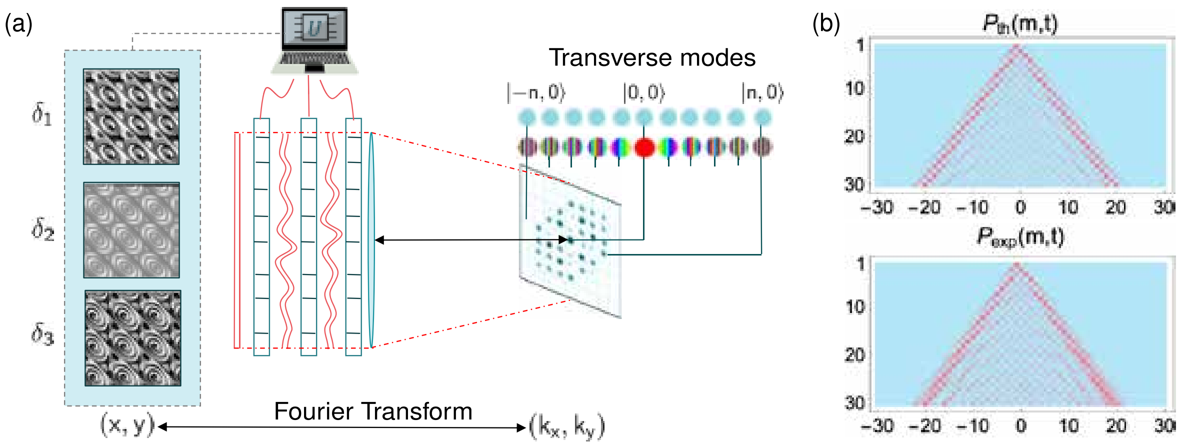


Figure 1: Fig. 1. (a) Compact free-space programmable photonic circuit implementing complex unitary operations mixing a large amount of transverse modes of light. The building blocks of the circuit are three SLMs, coupling polarization and spatial structure of the incoming photon state. (b) Theoretical and experimental time-resolved output distributions for 30 time steps of a 1D QW.

References

[1] W. Bogaerts et al., "Programmable photonic circuits," *Nature*, vol. 586, pp. 207–216 (2020).

[2] J. L. O'Brien, "Optical quantum computing," *Science*, vol. 318, pp. 1567–1570 (2007).

[3] A. D'Errico et al., "Two-dimensional topological quantum walks in the momentum space of structured light," *Optica*, vol. 7, no. 2, p. 108 (2020).

[4] F. Di Colandrea et al., "Ultra-long quantum walks via spin–orbit photonics," *Optica*, vol. 10, p. 324 (2023).

[5] M. G. Ammendola et al., "Large-scale free-space photonic circuits in two dimensions," *Adv. Photonics*, vol. 7, 016006-016006 (2025).

Up-Conversion Photon-Number-Resolving Detector

S. Cassina[1], A. Allevi[1]

[1] *Department of Science and High Technology, University of Insubria, Via Valleggio 11, I-22100 Como (Italy)*

The number of applications of infrared light has gained prominence in the field of quantum communication, thanks to the possibility to exploit the available fiber optics infrastructure working around 1.5 μm. However, single-photon detectors – and, even more, detectors with photon-number resolution – are lagging behind their visible counterparts. Although the potential of using photon-number-resolving (PNR) detectors in the quantum communication field has been recently demonstrated both theoretically [1] and experimentally [2, 3], the lack of detector solutions compared to the visible range hinders their widespread usage.

Our group has years of experience in exploiting commercial PNR detectors sensitive to visible light for quantum applications. In particular, we have recently demonstrated the suitability of Silicon photomultipliers (SiPM) for quantum optics and quantum information measurements [4]. Such detectors are compact, robust, low-cost and have low power requirements, thus being excellent candidates for quantum communication receivers. Their response, however, is limited to the visible and UV ranges.

This work is intended to be a first step toward the realization of a PNR detector, based on SiPMs and nonlinear interactions, for fiber-compliant telecommunication around 1.5 μm with coherent-state encoding.

Differently from other solutions, the main advantages of this detector are the operativity at room temperature and the high photon-number-resolving capability. While the former aspect fosters the portability of the device, the latter opens new perspectives in exploiting the mesoscopic intensity regime for quantum applications.

References

[1] M. Cattaneo, et Al., Phys. Rev. A, 2018, 98(1), 012333
[2] S. Cassina, et Al., Phys. Lett. A, 2025, 541, 130403
[3] A. Sanvito, et Al., Opt. Express, 2024, 32(22), pp. 39846–39859
[4] S. Cassina, et Al., EPJ Quantum Technol., 2021, 8(1), 4.

Bosonic Two-Stroke Heat Engines with Polynomial Nonlinear Coupling

G. Chesi[1]

[1] *QUIT Group, Dipartimento di Fisica, Università degli Studi di Pavia, Via Agostino Bassi 6, 27100 Pavia, Italy*

We discuss the thermodynamics of two-stroke heat engines where two bosonic modes a and b are coupled by the general nonlinear interaction $V_\theta = \exp\left(\theta a^{\dagger n} b^m - \theta^* a^n b^{\dagger m}\right)$ [**1**], which typically corresponds to nonlinear processes in quantum optics. We adopt the two-point measurement scheme [**2**], which is pictured and described in FIG. 1. Within this framework, we derive the distribution of the stochastic work, and hence the relative fluctuations (RFs) of the extracted work up to the second order in the coupling θ. We optimize the interaction V_θ with respect to n and m in order to provide the largest average work and/or the smallest fluctuations in the operational regime of the heat engine.
Then, we consider the specific cases $n = 2$, $m = 1$ and $n = 1$, $m = 2$ up to the fourth order in θ. Having fixed n and m, here we can perform the optimization of the average work and of the RFs over the frequencies of the bosonic modes and the temperatures of the reservoirs. Finally, we discuss the thermodynamic uncertainty relations (TURs) for these processes in relation with the order of the expansion of the unitary interaction V_θ. Importantly, the TURs bounding the RFs in the case $n = m = 1$ [**3**] are violated for $n > 1$ and/or $m > 1$.
A major motivation for this research has arised from the recent results obtained in Ref. [**4**] for the charging of quantum batteries, which is a different but related hot topic. There, the same coupling with $n = 1$ and energy-preserving constraint has been studied and the so-called genuine quantum advantage has been achieved with respect to the case $n = m = 1$, which is the interaction known as swap gate. This result suggests that the polynomial coupling V_θ could enhance the engine performance compared to the swap gate. We remark that polynomial couplings and the swap gate correspond to fundamentally different evolution maps: the swap gate preserves Gaussianity, while the polynomial coupling does not.

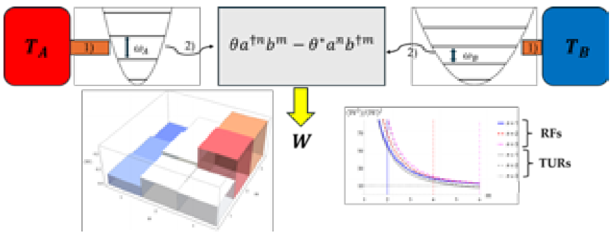


FIG. 1: Two-point measurement scheme applied to a bosonic two-stroke heat engine with polynomial coupling. Each cycle starts with the two harmonic oscillators A and B with Hamiltonians $H_A = \omega_A(a^\dagger a + \frac{1}{2})$ and $H_B = \omega_B(b^\dagger b + \frac{1}{2})$, at thermal equilibrium with two different pertaining reservoirs, with temperatures T_A and T_B such that $T_A > T_B$. Then the two systems are disconnected from their thermal baths and allowed to interact via the unitary V_θ. After the interaction, the two modes are reset to the initial equilibrium state via full thermalization by their respective baths, thereby completing one cycle of our two-stroke engine. The two panels reported in the figure display the average extracted work (left) and its RFs (right). The latters are compared with the pertaining TURs.

References

[1] G. Chesi, C. Macchiavello and M. F. Sacchi, arXiv:2502.17409 [quant-ph] (2025).

[2] M. Campisi, P. Hänggi and P. Talkner, Rev. Mod. Phys. **83**, 771 (2011).

[3] M. F. Sacchi, Phys. Rev. E **103**, 012111 (2021).

[4] G. M. Andolina, V. Stanzione, V. Giovannetti and M. Polini, arXiv: 2409.08627 [quant-ph] (2024).

Inhibition of circular Rydberg atoms decay: towards the realisation of quantum simulation of slow processes

Guillaume Cœuret Cauquil[1], Ankul Prajapati[1], Gauthier Rey[2], Michel Brune[1], Jean-Michel Raimond[1], Julien Mauchain[2], Igor Dotsenko[2]

[1] *Laboratoire Kastler Brossel, Collège de France, CNRS, ENS-PSL, Sorbonne Université, 11 place Marcelin Berthelot, F-75231 Paris, France.*
[2] *Laboratoire Collisions Agrégats Réactivité, Université Toulouse III - Paul Sabatier, 118 route de Narbonne, 31062 Toulouse, France.*

A fine description of many-body quantum systems has been shown to be a major task to better understand matter properties. Yet the computational complexity it brings prevents *ab-initio* calculation with classical computers. With a fully programmable quantum computer, one could imagine performing these computations with a reasonable complexity. Another possibility to study specific systems is to follow the path of quantum analogue simulation. By means of a fully controllable quantum system, one can indeed gain understanding about a complex target system, under the condition that their models share a formal equivalence [1].

Among all possibilities, simulation based on cold neutral atoms is a promising platform. More precisely, our group aims to realise a quantum simulator based on circular Rydberg atoms. By means of dipole-dipole interactions, it is indeed possible to design a system with the same Hamiltonian as that of a spin chain [2]. The interaction strength provided by the Rydberg state, around tens of MHz at a few µm, allows use of optical trapping techniques to spatially control the atoms [3]. A similar approach has already been used in experiments with low angular momentum states, showing promising results [4], but for which the study of slow processes is limited by the interaction cycle number. Another solution is to use states with maximal angular momentum (circular) which exhibit longer lifetime, reaching up to 30 ms for circular state $n = 50$ at cryogenic temperatures, two orders of magnitude above low angular momentum states in similar conditions. By means of two conductive plates, it is possible to inhibit the photon emission, leading to a much longer lifetime [5]. In fact, the ability to shape the vacuum mode structure surrounding the atoms gives us a new tool for controlling atoms. This idea has been applied to a room temperature experiment leading to a millisecond lifetime thanks to inhibition of stimulated and spontaneous emissions, the main limitation arising from black body radiations responsible for stimulated emission and absorption [6].

To further increase the lifetime of circular Rydberg state, it is possible to build a similar experiment in a cryogenic environment to reduce as much as possible black body radiations. This idea was suggested a few years ago, with theoretical simulations showing that lifetime can be expected to reach the minute range, which could lead to the study of processes with way slower dynamics [2]. My PhD project was to design and build such a cryogenic experiment, in which we cool down and transport ground state atoms in between two conductive plates. Then Rydberg excitation, circularisation and Rydberg atoms trapping will be performed before measuring the obtained lifetime through ionisation detection.

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

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

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

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

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

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

Cavity-Enhanced On-Demand Efficient Solid-State Quantum Memory

A. Das[1], L. Feldmann[1], S. Wengerowsky[1], S. Duranti[1], J. Hänni[1], S. Grandi[1] & H. de Riedmatten[1,2]

[1]*ICFO - Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, Av. Carl Friedrich Gauss 3, 08860 Castelldefels (Barcelona), Spain*
[2]*ICREA-Institució Catalana de Recerca i Estudis Avançats, 08015 Barcelona, Spain*

The realization of large-scale quantum networks requires the distribution of entanglement over long distances. Direct transmission is prohibitive due to losses in optical fibers. Quantum repeaters can overcome direct transmission loss and allow entanglement distribution at a continental scale. Most of the quantum repeater schemes rely on the storage of quantum states in quantum memories. For memories to be useful in practical implementations, they must exhibit several features, including a long storage time, a high storage efficiency, and a large multiplexing capability. Rare earth ion-doped crystals are arguably ideal candidates for building such optical quantum memories as they offer excellent coherence properties, long storage times, and high multiplexing capabilities. Here, we report on the realization of an efficient solid-state spin-wave quantum memory, with on-demand read-out, using the atomic frequency comb scheme (AFC) in a $Pr^{3+}:Y_2SiO_5$ (Pr:YSO) crystal embedded in an impedance-matched cavity. We demonstrate operation at the single-photon level by storing weak coherent states with an efficiency up to 40 %. We investigate the enhancement of the incoherent noise due to the impedance-matched cavity and characterize the quantum memory performance for different storage bandwidths and control pulse power. Finally, we confirm the quantum nature of our memory by storing a heralded single photon from a non-degenerate SPDC source and achieving non-classical correlations between the heralding and the retrieved photon. Our results demonstrate that impedance-matched AFC spin-wave quantum memories with on-demand read-out can be used for experiments involving the storage of photonic quantum states and serve as a resource for quantum networks and quantum repeaters.

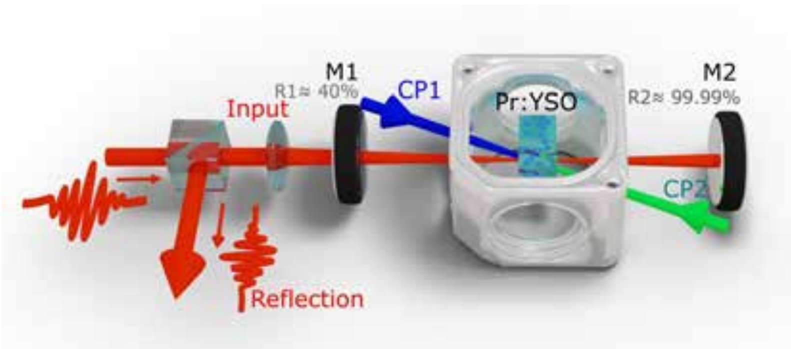


FIG. 1: Schematic of the experimental setup for spin-wave AFC storage.

References

[1] S. Duranti, Optics Express 32 (15), 26884-26895 (2024).

[2] M. Afzelius et al, Phys. Rev. A, 79, 052329 (2009)

[3] M. Afzelius, and C. Simon, Phys. Rev. A, 82, 022310 (2010)

Self organisation and metastability of cavity bosons beyond the adiabatic elimination approximation

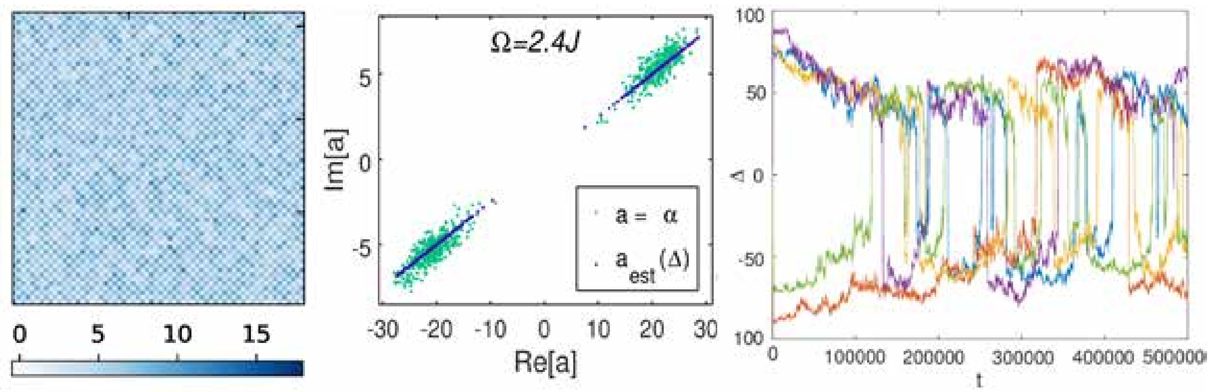
G. Orso[1], **J. Zakrzewski**[2], **P. Deuar**[3*]

[1] *Université Paris Cité, Laboratoire Matériaux et Phénomènes Quantiques (MPQ), CNRS, F-75013, Paris, France*
[2] *Institute of Theoretical Physics and Mark Kac Complex Systems Research Center, Jagiellonian University in Krakow, ul. Lojasiewicza 11, 30-348 Kraków, Poland*
[3*] *Institute of Physics, Polish Academy of Sciences, Aleja Lotników 32/46, 02-668 Warsaw, Poland*
deuar@ifpan.edu.pl

Phase-space formulations of quantum mechanics like the positive-P and truncated Wigner can give access to the full quantum behaviour of very large systems. In particular, the full distribution of single-shot configurations can be obtained from a stochastic simulation. This is particularly useful for dissipative systems for which direct simulation is harder but phase space methods become stable [1].

In a recent work [2] we have looked at the very long-time behaviour and self-organisation of weakly interacting bosons in a 2d optical lattice coupled to a lossy cavity, in the regime of high filling similar to experiments at ETH [3]. The truncated Wigner representation allows us to go orders of magnitude longer in time compared to earlier numerical work. It takes into account the dynamics and correlation of the cavity mode, quantum fluctuations, and self-organisation of individual runs, and has been benchmarked by us for this system.

We observe metastability at very long times and superfluid quasi-long range order, in sharp contrast with the true long range order found in the ground state of the Bose-Hubbard model with extended interactions obtained by adiabatically eliminating the cavity. The metastability appears to be dependent on the relaxation of the adiabatic elimination constraint. As the strength of the cavity coupling increases in a superfluid, the system first becomes (lattice) supersolid at the superradiant transition and then turns into a charge-density wave via the BKT mechanism. Notably, experimental preparation times have often been comparable with the very long times simulated here, so the metastable effects may be relevant in practice.



Behaviour of a self-organised lattice supersolid of 2d cavity bosons. Left: checkerboard density pattern; Centre: cavity field amplitudes in the full quantum simulation (turquoise) and adiabatic elimination approach (blue); Right: checkerboard order parameter Δ for several runs over long times. Note the slow bistable switching after reaching the long-time ensemble [2].

References

[1] P. Deuar, A. Ferrier, M. Matuszewski, G. Orso, M. H. Szymanska, *Fully quantum scalable description of driven-dissipative lattice models*, PRX Quantum **2**, 010319 (2021).

[2] G. Orso, J. Zakrzewski, P. Deuar, *Self-organized cavity bosons beyond the adiabatic elimination approximation*, Physical Review Letters **1xx**, to appear (2025); arXiv:2312.10502

[3] R. Landig, L. Hruby, N. Dogra, M. Landini, R. Mottl, T. Donner, and T. Esslinger, *Quantum phases from competing short- and long-range interactions in an optical lattice*, Nature **532**, 476 (2016).

CRITICAL QUANTUM METROLOGY WITH KERR RESONATORS

Roberto Di Candia[1,2]
[1]*Dpt. of Information and Communications Engineering, Aalto University, Espoo, 02150 Finland*
[2] *Dip. Fisica, University of Pavia, via Bassi 6, I-27100 Pavia, Italy*

Critical quantum sensing (CQS) is by now a well-established approach, based on the exploitation of quantum properties spontaneously developed in proximity of phase transitions. Numerous theoretical studies and first experimental demonstrations show that a quantum-enhanced sensing precision can be achieved by exploiting static or dynamical properties of many-body systems in proximity of the critical point [1]. It has been shown [2] that CQS protocols can also be implemented using finite-component phase transitions (FCPTs), where the thermodynamic limit is replaced with a rescaling of the system parameters.
Here, we discuss [3,4] quantum sensing protocols with parametrically pumped Kerr resonators in a thermal dissipative environment. We show the optimality of such protocols with respect to metrological optimal precision bounds [5], and discuss how collective advantage can be achieved when the Kerr resonators are coupled [6]. We then report on the experimental implementation [7,8] of a driven-dissipative CQS protocol with a superconducting resonator shunted by a SQUID, with direct applications in magnetometry and superconducting-qubit readout.

[1] V. Montenegro, C. Mukhopadhyay, R. Yousefjani, S. Sarkar, U. Mishra, M.G.A. Paris, A. Bayat, arXiv:2408.15323 (2024)

[2] L. Garbe, M. Bina, A Keller, M.G.A. Paris, S. Felicetti, *Physical Review Letters* **124**, 120504 (2020)

[3] R. Di Candia, F. Minganti, K.V. Petrovnin, G.S. Paraoanu, S. Felicetti, *npj Quantum Inf.* **9**, 23 (2023)

[4] U. Alushi, W. Górecki, S. Felicetti, R. Di Candia, *Physical Review Letters* **133**, 040801 (2024)

[5] W. Górecki, F. Albarelli, S. Felicetti, R. Di Candia, L. Maccone, arXiv:2409.18791 (2024)

[6] U. Alushi, A. Coppo, V. Brosco, R. Di Candia, S. Felicetti, *Communications Physics* **8** (1), 74 (2025).

[7] G. Beaulieu, F. Minganti, S. Frasca, M. Scigliuzzo, S. Felicetti, R. Di Candia, P. Scarlino, aXiv:2409.19968 (2024) [Accepted in *PRX Quantum*]

[8] G. Beaulieu, F. Minganti, S. Frasca, V. Savona, S. Felicetti, R. Di Candia, P. Scarlino, *Nature Communications* **16**, 1954 (2025)

Fully reconfigurable quantum state interference in a frequency encoding

P. Folge[1],A. Bhattacharjee[1],M. Stefszky[1],S. Lengeling[1],B. Brecht[1],C. Silberhorn[1]

[1]*Paderborn University, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Paderborn, Germany*

The scaling of linear optical quantum networks, as used in e.g. (Gaussian) boson sampling, poses a challenge due to growing experimental setups and large numbers of required components. Here, we demonstrate a novel platform for the implementation of such networks in a frequency bin encoding which only requires two-nonlinear waveguides for an experimental realization of the network [**1**]. We achieve this by making use of an engineered sum-frequency generation process, in a so-called quantum pulse gate (QPG), which allows to interfere input frequency bins in fully programmable superpositions.

In our proof of principle experiment (see Fig. 1a) we interfere squeezed states, provided by a type-0 parametric down conversion source (PDC). In the QPG we convert three of these bins and map them to the same output frequency mode, which enables quantum state interference. The superposition into which these squeezed states are mapped is fully controlled by spectral shaping of the pump pulses of the QPG with an SLM based pulse shaper. To verify the resulting quantum state interference in the QPG's output we perform second order correlation function ($g^{(2)}$) measurements. In the experiment we keep the phases of the outer pump bins fixed and vary the phase of the central bin. The implemented interference is then equivalent to the spatial domain network depicted in Fig. 1b where the phase of the central channel determines whether the networks output interferes to a thermal state ($g^{(2)} = 2$) or a single mode squeezed state ($g^{(2)} > 3$). In our measurement we clearly observe the transition between these regimes in good agreement with our theoretical model, which demonstrates the quantum state interference. The dimensionality of the system can easily be increased by adding more pump bins, no change of hardware is required. Moreover, with the use of the recently demonstrated multi-output QPGs [**2**] it also becomes possible to access multiple network outputs simultaneously, which makes our scheme a promising platform for the resource efficient implementation of large linear quantum networks.

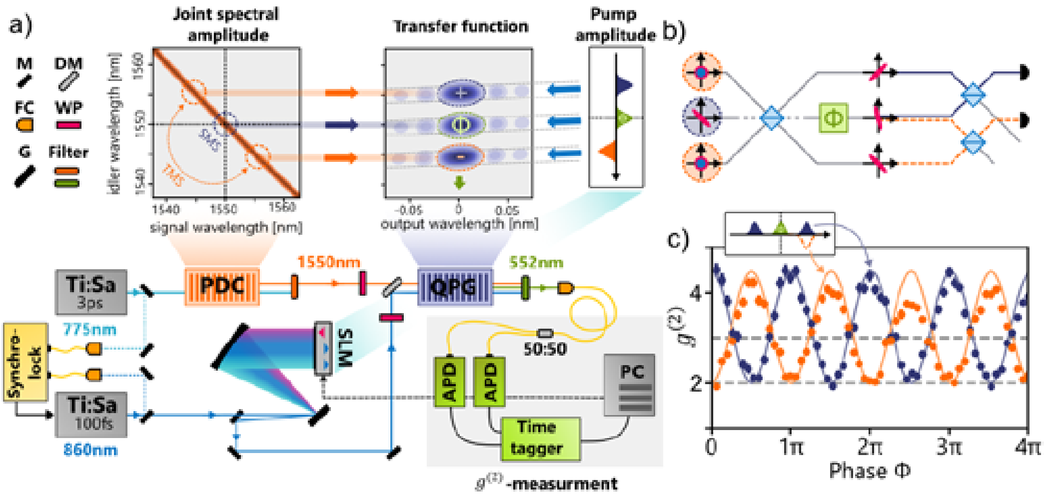


FIG. 1: a) Schematic depiction of the experimental setup. Here, the squeezed states in three frequency bins are interfered. b) the analogous spatial network implementing the same quantum state interference. c) Correlation function measurement for a varied phase of the central bin and comparison to a theoretical model (solid lines).

References

[1] P. Folge et al., PRX Quantum **5**, 040329 (2024)

[2] L. Serino et al., PRX Quantum **4**, 020306 (2023)

Transfer and conversion of intra- and inter-mode correlations in a system of coupled bosonic modes

J. Bembenek, Z. Ficek

Quantum Optics and Engineering Division, Institute of Physics, University of Zielona Góra, 65-516 Zielona Góra, Poland

The creation, transfer and conversion of quantum correlations play a major role in operation of quantum networks. Their presence and/or creation is crucial for the generation and transfer of coherence and entanglement between different parts of the system. In this presentation we will address this problem and consider a continuous variable Gaussian system composed of two bosonic modes a and b, which can be coupled through fundamentally dissimilar physical processes, the linear (beamsplitter) type interaction or the nonlinear (parametric down conversion) interaction or by both simultaneously present in the system [1]. We include decoherence (damping) expected for modes interacting with their environments. The down-conversion process is known to entangle modes being in classical states [2,3], and the linear interaction is known to generate entanglement only if the modes are in nonclassical states [4].

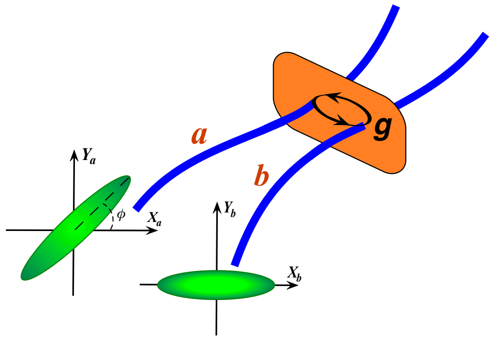


FIG. 1: Two single-mode squeezed fields are launched into modes a and b. The orientation of the squeezing ellipse of mode b is fixed whereas the ellipse of mode a can be rotated with angle ϕ. The modes are subjected to interact with each other with the interaction strength g.

We find several interesting and unusual results for the transfer and conversion of the correlations between the modes. For example, the processes of transferring the intra-mode two-photon correlations $\langle aa \rangle$ and $\langle bb \rangle$ and conversion of the correlations into inter-mode correlations, the one-photon $\langle a^{\dagger} b \rangle$ and two-photon $\langle ab \rangle$ correlations depend strongly on the type of the interaction between the modes, mutual orientation of the squeezing ellipses, and not necessary equal numbers of photons and degrees of correlations present initially in the modes. A non-zero one-photon correlations results in the coherence of the modes whereas a non-zero two-photon correlation may result in entanglement of the modes. The degrees of the one- and two-photon coherences depend strongly on the degree of squeezing of the mode fluctuations, i.e. whether the modes exhibit classical or quantum squeezing. In addition, we show that the inter-mode correlations can be created not necessary by the conversion of the existing intra-mode correlations. This happens in the case of the nonlinear interaction between the modes where the creation of the two-photon correlations $\langle ab \rangle$ is found to be independent of the presence of the intra-mode correlations which, on the other hand, are converted by this nonlinear process into one-photon correlations. Moreover, the process of conversion of the intra-mode correlations into inter-mode correlations occurs with a rate different than that the intra-mode correlations are reduced.

References

[1] J. J. Slim, *et al.*, Nature **627**, 767 (2024).

[2] M. J. Collett and C.W. Gardiner, Phys. Rev. A **30**, 1386 (1984).

[3] P. Lahteenmki, G. S. Paraoanu, J. Hassel, and P. J. Hakonen, Nat. Commun. **7**, 12548 (2016).

[4] M. S. Kim, W. Son, V. Buzek and P. L. Knight, Phys. Rev. A. **65**, 032323 (2002).

CEWQO29 - Necessity of non-Gaussianity in the joint Estimation of Position and Momentum with arbitrarily high precision

Massimo Frigerio

Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, 4 place Jussieu, F-75252 Paris, France

M. Frigerio[1], M. G. A. Paris[2], C. E. Lopetegui[1] and M. Walschaers[1]

[1] *Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, 4 place Jussieu, F-75252 Paris, France*
[2] *Dipartimento di Fisica "Aldo Pontremoli", Università degli Studi di Milano, I-20133 Milano, Italy*

Quantum mechanics forbids the simultaneous measurement of the position and linear momentum quadratures of a bosonic mode with arbitrarily high accuracy, but this constraint does not apply to shifts in the expectation values of those observables. In this work we address the joint estimation of such shifts, generated by non-commuting operators, showing that leveraging non-Gaussianity enables their simultaneous estimation with arbitrarily high precision and arbitrarily low quantum incompatibility. Specifically, using the tools of multi-parameter quantum metrology, we demonstrate that any pure non-Gaussian state provides an advantage over all Gaussian states, whether pure or mixed. Moreover, properly tuned non-Gaussian mixtures of Gaussian states can also serve as a resource. The advantage over Gaussian models is linked to the classical indistinguishability between the parameters, also known as sloppiness, which is lower bounded for all Gaussian states. We also find that neither quantum non-Gaussianity nor Wigner negativity are sufficient, nor necessary, to guarantee such a metrological advantage, in stark contrast with other applications in which non-Gaussianity proved to be resourceful.

References

[1] M. G. A. Paris - *Quantum Estimation for Quantum Technology* - Int. J. Quantum Inf., 7, 124-137 (2009).

[2] A. Carollo, B. Spagnolo, A. A. Dubkov and D. Valenti - *On quantumness in multi-parameter quantum estimation* - J. of Stat. Mech.: Theory and Experiment 9, 094010 (2019).

[3] Deng, X., Li, S., Chen, Z.-J., Ni, Z. et al. - *Quantum-enhanced metrology with large Fock states* - Nat. Phys. 12, 20, 1745-2481 (2024).

[4] Park, K., Oh, C., Filip, R. and Marek, P. - *Optimal Estimation of Conjugate Shifts in Position and Momentum by Classically Correlated Probes and Measurements* - Phys Rev. Appl. 18, 1, 014060 (2022).

Quantum Metrology in the Ultrastrong Coupling Regime of Light-Matter Interactions: Leveraging Virtual Excitations without Extracting Them

Karol Gietka

Institute For Theoretical Physics,
University of Innsbruck, Austria

Virtual excitations, inherent to ultrastrongly coupled light-matter systems, induce measurable modifications in system properties, offering a novel resource for quantum technologies. In this work, we demonstrate how these virtual excitations and their correlations can be harnessed to enhance precision measurements, without the need to extract them. Building on the paradigmatic Dicke model, which describes the interaction between an ensemble of two-level atoms and a single radiation mode, we propose a method to harness hybridized light-matter modes for quantum metrology. Our results not only highlight the potential of virtual excitations to surpass classical precision limits but also extend to a broad range of ultrastrongly coupled systems.

Inelastic Scattering of a Photon by a Quantum Phase-Slip

L. I. Glazman

Department of Physics and Yale Quantum Institute, Yale University, New Haven, Connecticut 06520, USA

Spontaneous decay of a single photon is a notoriously inefficient process in nature, regardless of the frequency range. We found that a quantum phase-slip fluctuation in a high-impedance superconducting waveguide can “split” a single incident microwave photon into a large number of lower-energy photons with a near-unit probability. The underlying inelastic photon-photon interaction has no analog in the conventional non-linear optics theory. Instead, the photon splitting rates are evaluated within the framework of the quantum many-body theory, where we introduce a new model of a quantum impurity in a Luttinger liquid [1].

Our theory allowed us to explain, without adjustable parameters, the decay rates of the microwave photons propagating through a Josephson junction array [2]. Furthermore, it enabled us to elucidate the microwave spectroscopic signatures of the so-called Schmid transition, the simplest paradigmatic example of a quantum phase transition [1, 3]. The first indication of such a transition in a high-impedance array was recently reported in [4].

Our results offer a new way of quantum many-body simulations by linking circuit quantum electrodynamics to critical phenomena in two-dimensional boundary quantum field theories, important in the physics of strongly correlated systems.

[1] M. Houzet and L. I. Glazman, Phys. Rev. Lett. **125**, 267701 (2020); https://doi.org/10.1103/PhysRevLett.125.267701.

[2] R. Kuzmin, N. Grabon, N. Mehta, A. Burshtein, M. Goldstein, M. Houzet, L. I. Glazman, and V. E. Manucharyan, Phys. Rev. Lett. **126**, 197701 (2021); https://doi.org/10.1103/PhysRevLett.126.197701.

[3] Manuel Houzet, Tsuyoshi Yamamoto, and Leonid I. Glazman, Phys. Rev. B **109**, 155431 (2024); https://doi.org/10.1103/PhysRevB.109.155431.

[4] Kuzmin, R., Mehta, N., Grabon, N. et al., Nat. Phys. (2024); https://doi.org/10.1038/s41567-024-02695-7

Control of Mechanical Systems in the Quantum Regime

Piotr T. Grochowski[1]

[1]*Department of Optics, Palacký University, 17. listopadu 1192/12, 771 46 Olomouc, Czech Republic*

Contrary to the qubit-based, discrete systems, continuous quantum platforms enable encoding increased complexity into fewer physical systems through large-scale non-Gaussian states. Motion, as an exemplary continuous degree of freedom, underpins numerous nonlinear phenomena—from Cooper pair dynamics and optical wave packets to the macroscopic levitated objects. Despite significant progress in harnessing mechanical nonlinearities and generating quantum non-Gaussian states in low-energy regimes, their full potential remains untapped. Achieving high-quality, high-energy, and spatially large quantum non-Gaussian states is essential for progress in quantum sensing, quantum simulations, and foundational tests of quantum mechanics.

We explore the following control schemes for mechanical degrees of freedom in nonlinear systems, including atoms or particles trapped in nonharmonic potentials or clamped solid-state oscillators with available spin-motion coupling. **(i) Nonharmonic potential modulation.** First, we present a theoretical proposal for preparing and manipulating a state of a single continuous-variable degree of freedom confined to a nonharmonic potential [1]. By utilizing optimally controlled modulation of the potential's position and depth, we demonstrate the generation of various non-Gaussian states, as well as the implementation of arbitrary unitaries within a selected two-level subspace [Fig. 1(a)]. **(ii) Macroscopic quantum states of levitated nanoparticles.** Second, we introduce a method for the rapid preparation of the center of mass of a levitated particle in a macroscopic quantum state—one that is delocalized over a length scale much larger than its zero-point motion and has no classical analog [2]. This state is prepared by letting the particle evolve in a static double-well potential after a sudden switchoff of the harmonic trap, following initial center-of-mass cooling to a sufficiently pure quantum state [Fig. 1(c)]. **(iii) Phase-insensitive force sensing.** Finally, we consider a force-sensing scheme where the induced phase-space displacement direction is randomized and an excitation number resolving measurement is performed [3]. By applying quantum optimal control in a spin-boson system, we identify number-squeezed cat states as the optimal choice for maximizing force sensitivity under lossy dynamics and the finite system controllability [Fig. 1(b)].

These studies highlight different approaches to motion control—either leveraging intrinsic nonharmonicity in the confining potential or coherent coupling to an external nonlinear system. Our results provide a versatile control toolbox for nonlinear continuous-variable quantum systems, including scenarios with weak intrinsic nonharmonicity or limited external coherent coupling. As new mechanical platforms, such as levitated nanoparticles and bulk wave resonators, continue to advance into the quantum regime, developing robust control strategies for their motion becomes crucial for both fundamental physics and technological applications. Our work paves the way toward universal control of a broad class of continuous quantum systems, encompassing both massive mechanical oscillators and massless quantum fields such as optical and microwave resonators.

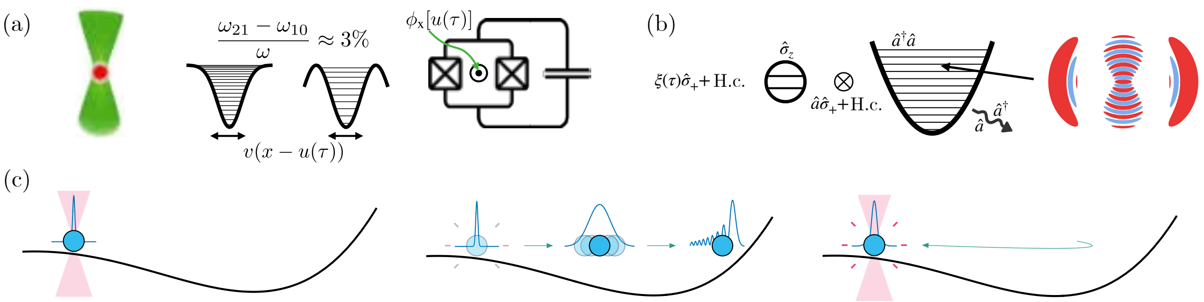


Figure 1: (a) Examples of continuous nonlinear systems that can be optimally controlled without the need of auxiliary systems—single atoms in optical tweezers and fluxt-unable transmons. (b) In an optimally controlled spin-boson model with finite controllability and decoherence, a family of number-squeezed cat states maximizes achievable sensitivity for weak force sensing. (c) Schematic representation of the protocol for the preparation of a macroscopic quantum state of a nanoparticle utilizing hybrid potential.

References

[1] **PTG**, H. Pichler, C. A. Regal, O. Romero-Isart, *Quantum control of continuous systems via nonharmonic potential modulation*, arXiv:2311.16819,

[2] M. Roda-Llordes, A. Riera-Campeny, D. Candoli, **PTG**, O. Romero-Isart, *Macroscopic quantum superpositions via dynamics in a wide double-well potential*, Phys. Rev. Lett. **132**, 023601 (2024)

[3] **PTG**, R. Filip, *Optimal phase-insensitive force sensing with non-Gaussian states*, arXiv:2505.20832.

Disordered Gauge Fields for Atomic Bose Gases

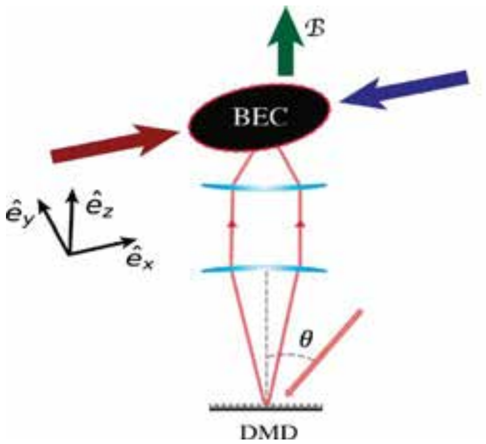
A. M. Piñeiro[1], E. Gvozdiovas[1,2], E. D. Mercado-Gutierrez[1], I. B. Spielman[1]

[1] *Joint Quantum Institute, National Institute of Standards and Technology and University of Maryland, Gaithersburg, MD 20899, USA*

[2] *Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio Ave. 3, LT-10257 Vilnius, Lithuania*

The ongoing study of disordered systems has so far revealed a variety of complex phenomena, such as Anderson localization [1], loss of phase coherence [2], and many-body localization [3]. Disorder remains a highly active topic of research as its effects are somewhat elusive due to the emergence of different properties depending on the dimensionality, size and complexity of disordered physical systems.

In this work, we investigate disorder in the context of vector potentials for Bose-Einstein condensates. By employing a digital mirror device, we engineer position dependent random vector potentials for an ultracold gas of bosonic Rubidium-87 in a Raman coupling scheme (Fig. 1). We experimentally and theoretically investigate the dynamics of the atomic cloud on time scales where single particle effects are dominant, as well as the temporal evolution of the Raman dressed state in the regime of many body interactions. We consider the limitations of our imaging system, such as the numerical aperture and optical aberrations, to understand the statistical properties of various potentials cast upon the ultracold gas. This work further advances the experimental toolbox for manipulating ultracold quantum gases and provides valuable insight into disordered many body quantum physics.



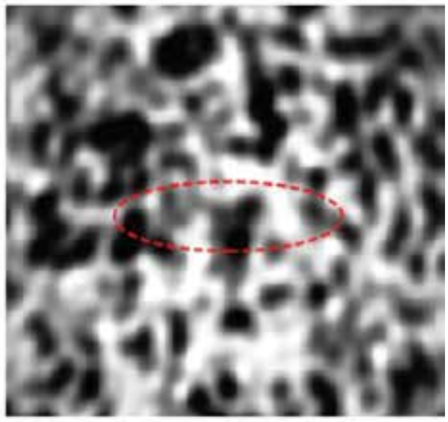


FIG. 1: Left: counter-propagating Raman coupling scheme with an upgoing beam engineered using a digital mirror device; Right: a disordered pattern of light as simulated after passing through the imaging system. The red dashed line indicates the spatial extent of the in-situ atomic cloud.

References

[1] P. W. Anderson, Phys. Rev. 109, 1492 (1958).

[2] M. C. Beeler, M. E. W. Reed, T. Hong, S. L. Rolston, New J. Phys. 14, 073024 (2012).

[3] K. Suthar, P. Sierant, J. Zakrzewski, Phys. Rev. B 101, 134203 (2020).

Capacity of phase sensitive preamplified receivers

A. Mikos-Nuszkiewicz[1,2,3], M. Jarzyna[1,3], R. Filip[3]

[1] *Centre for Quantum Optical Technologies, Centre of New Technologies, University of Warsaw, Banacha 2c, 02-097 Warsaw, Poland*
[2] *Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*
[2] *Department of Optics, Palacky University, 17. listopadu 1192/12, 771 46 Olomouc, Czech Republic*

Detection of optical signals is a fundamental task, lying at the heart of many technical and scientific applications. However, in many scenarios extraction of the desired information from the signal becomes a cumbersome task. A basic example of such a situation occurs in the weak signal regime, where the noise may easily overcome the received signal power. A typical remedy for such a problem is to include a preamplifier in the receiver architecture which allows to increase the signal level to values noticeably exceeding the detection noise.

A conventional preamplification involves a phase insensitive amplifier. Such a device uniformly amplifies both quadratures of light, but even in the ideal case introduces an inevitable additive quantum noise that is proportional to the amplifier gain. On the other hand, one can use a more sophisticated phase sensitive amplifier (PSA) which amplify only one of the input quadratures at the cost of deamplifying the other one, but crucially is in principle noiseless. Importantly, in the context of optical signals reception, PSA has been recently demonstrated to enable quantum state tomography of broadband states when used as a preamplifier together with direct detection [**1**, **2**]. Since it is known that the latter measurement technique is particularly useful in weak signal optical communication regime, offering high photon information efficiency [**3**], it may be also benefitial to use PSA preamplification in this context as well, a problem investigated so far only for optical quadrature receivers [**4**].

In this work, we theoretically analyze the improvement provided by the PSA preamplification in the capacity of quadrature and direct detection receivers. We show that an amplified photon number resolving (PNR) receiver may perform closely or even outperform the corresponding homodyne receiver, especially in the low power level, typical e.g. for deep-space missions, or when the system operates at high-end bandwidths, of the order of several hundreds of GHz. We show that this enhancement persists, even in the presence of finite photon number resolution or when one substitutes the PNR detector with a much less demanding intensity measurement, like a PiN diode. We also investigate how squeezed states may improve the communication rates of preamplified receivers in links exhibiting low channel losses, relevant in instances involving short-haul communication links.

References

[1] Y. Shaked, Y. Michael, R. Z. Vered, L. Bello, M. Rosenbluh, and A. Peer, Nature Communications **9**, 609 (2018).

[2] M. Kalash and M. V. Chekhova, Optica **10**, 1142 (2023).

[3] M. Jarzyna, Phys. Rev. A **104**, 022605 (2021).

[4] R. Larsson, R. U. Weerasuriya, and P. A. Andrekson, Optica **11**, 1497 (2024).

Probing Two-Body Contact Dynamics near a Narrow Feshbach Resonance

A. Journeaux[1], M. Lecomte[1], J. Veschambre[1], E. Uzan[1], J. Dalibard[1], R. Lopes[1]

[1]*Laboratoire Kastler Brossel, Collège de France, CNRS, ENS-Université PSL, Sorbonne Université, 11 Place Marcelin Berthelot, 75005 Paris, France*

We study the real-time evolution of the two-body contact in a strongly interacting Bose gas of dysprosium by exploiting narrow magnetic Fano–Feshbach resonances under optical control. Using spin-dependent light shifts, we implement rapid, reversible tuning of the dimer bound state energy. To enhance sensitivity to early-time dynamics, we repeatedly modulate the closed-channel bound state energy, accumulating interaction-induced atom losses that facilitate direct observation of short-range correlation buildup. We find that the contact equilibrates on a timescale governed by the gas temperature, with a scaling that differs from that of its equilibrium value, revealing a temperature-dependent rate for the formation of correlations.

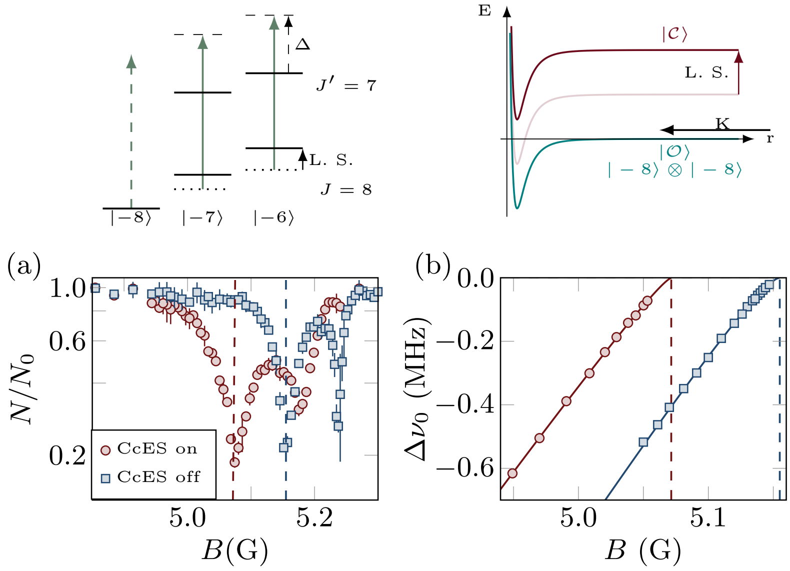


Figure 1: Schematic representation of a Fano-Feshbach Resonance (FFR) dressing with a laser beam. The figure illustrates the ground state manifold light shift and the resulting light shift of the closed channel molecular energy. (a) Loss features in the presence and absence of the closed-channel energy shift (CcES) laser, showing the optical displacement of the magnetic Feshbach resonance. (b) Determination of $\delta\mu$, B_0, and $R_\star$ from the evolution of the dimer energy, $h\Delta\nu_0$, as a function of B.

Environment-Assisted Generation of Non-Gaussian Wavepacket Quantum States

Maryam Khanahmadi 1, and Klaus Mølmer 2

1 Department of Microtechnology and Nanoscience, Chalmers University of Technology, 412 96 Gothenburg, Sweden
2 Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen,Denmark

We present a hardware-efficient approach to prepare single-mode travelling wave packets in non-Gaussian bosonic states with a superconducting circuit platform. Such states enable secure deterministic quantum communication between distant quantum processor units. Rather than first producing the non-Gaussian states in a cavity mode by a nonlinear process and subsequently releasing it to a waveguide, we propose and analyze a scheme that applies a combination of linear and nonlinear interactions and losses to form and emit the states in wave packets, controlled by the coherent excitation of the system. The system is subject to a non-linear anti-Hermitian Hamiltonian of high order due to losses of lower order, and our proposal enables efficient and deterministic creation of propagating two- and four-component cat states, grid states, and entangled pair-cat states.

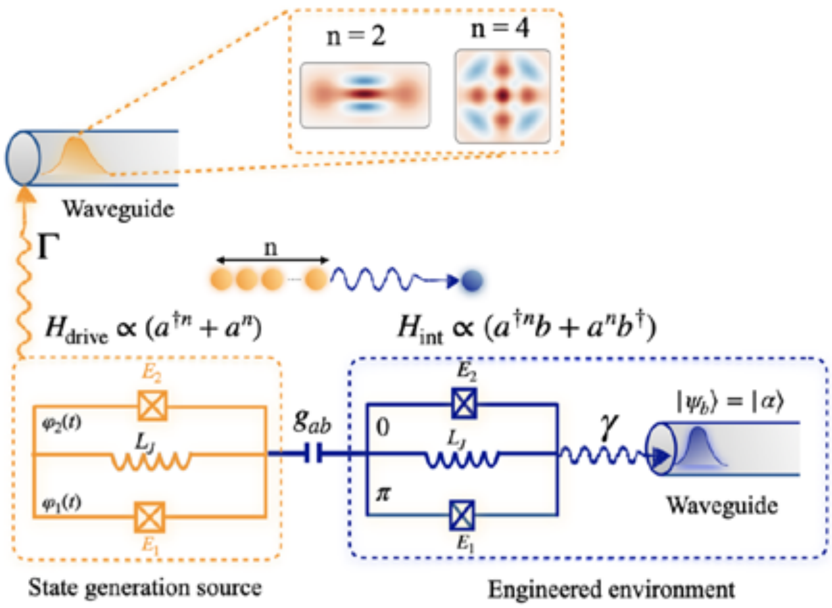


FIG. 1. Engineering non-linear dissipation for preparation of travelling cat state wave packets. The state is prepared in the bosonic a-mode (left orange circuit) which is capacitively coupled to the buffer b-mode (right blue circuit), through the controllable interaction $H_{\text{int}} = g_{ab}(a^{\dagger n} b + a^n b^\dagger)$. These bosonic modes experience constant, linear transmission to two different waveguides through the coupling rates Γ, γ where $\gamma \gg \{\Gamma, g_{ab}\}$. In conjunction with an n-photon drive, $H = \Omega_d(t)(a^{\dagger n} + a^n)$, the n-photon loss of the a-mode, mediated by the b-mode, leads to the emission of propagating n-component cat states in the upper waveguide.

Paper link: arXiv:2504.04513

Optical Key Distribution with a Noisy Laser Source

M. Kucharczyk[1,2], M. Lasota[3], M. Jarzyna[2,4], K. Banaszek[1,2,4], R. Demkowicz-Dobrzański[1]

[1] *Faculty of Physics, University of Warsaw, Poland*
[2] *Quantum Optical Technologies sp. z o.o., Rzeszów, Poland*
[3] *Institute of Physics, Nicolaus Copernicus University, Toruń, Poland*
[4] *Centre for New Technologies, University of Warsaw, Poland*

Optical Key Distribution (OKD) [1] is a promising approach to secure optical communication at the physical layer, providing resistance to passive eavesdropping with modest hardware requirements. The recently proposed [2] and experimentally demonstrated [3] intensity-modulation/direct-detection (IM/DD) OKD protocol enables the generation of cryptographic keys between two legitimate users, Alice and Bob. This approach, shown in Fig. 1(a), employs finely modulated optical signals, followed by reverse reconciliation and privacy amplification to extract a secure key. In practical implementations, laser sources inherently exhibit intensity noise, which may introduce correlations in recipients' measurements, thus increasing eavesdropper's knowledge of the secret key. Consequently, these correlations reduce the achievable secret key rate, as the key distillation protocol must account for and eliminate eavesdropper's potential knowledge.

In this contribution, we analyze the impact of source intensity noise on OKD by comparing three modulation and decoding schemes: Gaussian and binary modulation, both with soft decoding, as well as binary modulation with hard decoding (dual-threshold discrimination). The results of optimization, depicted in Fig. 1(b), are not as intuitive as in conventional data transmission, where soft-decoded Gaussian modulation typically maximizes the information rate. Our results demonstrate that, in certain regions, hard decoding outperforms both Gaussian and binary modulation with soft decoding in maximizing the secret key rate. These findings highlight the need to consider source intensity noise and eavesdropper constraints when implementing the OKD protocol in practical scenarios.

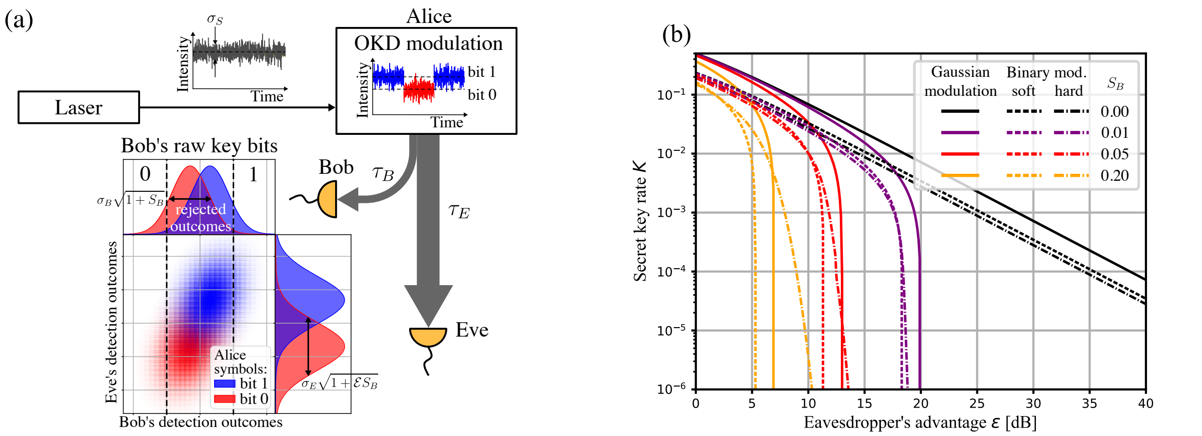


Figure 1: (a) **OKD Scheme Overview**: A laser signal with intensity noise σ_S is finely modulated to transmit two bits (0, 1). The optical signal from Alice is split, with Bob and Eve receiving fractions τ_B and τ_E, respectively. The signal is directly detected by Bob and Eve, with detection noise variances σ_B^2 and σ_E^2. The eavesdropper's advantage is $\mathscr{E} = (\tau_E \sigma_B)^2/(\tau_B \sigma_E)^2$, and relative source noise contribution is $S_B = (\tau_B \sigma_S/\sigma_B)^2$. (b) **Secret Key Rate Comparison**: Optimized secret key rate K is shown for Gaussian modulation (solid line), binary modulation with soft decoding (dashed line), and binary modulation with hard decoding (dot-dashed line). Larger S_B indicates higher source intensity noise and stronger measurement correlations.

References

[1] T. Ikuta and K. Inoue, New J. Phys. **18**, 013018 (2016)

[2] K. Banaszek, M. Jachura, P. Kolenderski, and M. Lasota, Opt. Express **29**, 43091-43103 (2021)

[3] M. Jachura, et al., Optical Fiber Communication Conference (OFC) 2024, paper **W1H.6**

Hierarchical verification of non-Gaussian coherence in bosonic quantum states

Lukáš Lachman[1,2], **Beate E. Asenbeck**[1], **Ambroise Boyer**[1], **Priyanka Giri**[1], **Alban Urvoy**[1], **Radim Filip**[2] **and Julien Laurat**[1]

[1]*Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, 4 Place Jussieu, 75005 Paris, France*

[2]*Department of Optics, Palacký University, 17. Listopadu 12, 771 46 Olomouc, Czech Republic*

Understanding and controlling the quantum coherence is a crucial prerequisite for realizing quantum information processing and error correction. Accomplishing such tasks requires access to advanced quantum resources reaching a highly nonclassical regime going beyond the Gaussian states. The stellar hierarchy was introduced as a tool characterizing non-Gaussian resources [1] and employed for ordering states approaching the Fock states. We advance this evaluation by specifying a task in which the quantum coherence represents a figure-of-merit instead of achieving a high Fock state. We study situations when quantum coherence outperforms the coherence emerging the Gaussian processes that act on specific free states, which fail in the consider task [2,3]. We propose a hierarchy that classifies a degree of the quantum non-Gaussian coherence and test feasibility of the respective criteria by applying them to state-of-the-art photonic states. We certify that the experimentally generated states overcome the limits of the coherence reached by Gaussian evolution of any Fock state.

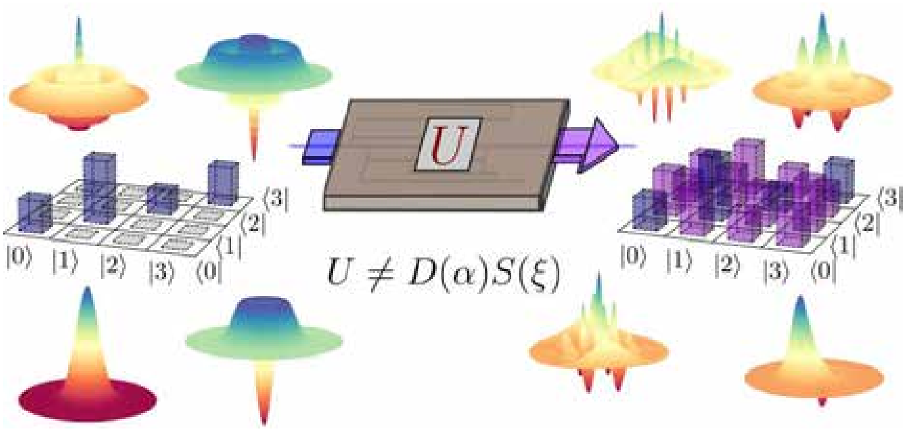


Fig. 1: Certification of the quantum non-Gaussian coherence recognizes situations when an output in a coherence-dependent task outperforms any result achieved by Gaussian evolution of an arbitrary Fock state.

References

[1] U. Chabaud, D. Markham, and F. Grosshans, Phys. Rev. Lett. **124**, 063605 (2020).

[2] arXiv:2501.14032

[3] arXiv:2501.14033

Control and Scattering Properties in Dipolar Spin Mixtures.

Louis Lafforgue[1], **J.J. Arfor Houwman**[1], **Sarah Embach**[3], **Nirav P. Mehta**[3], **Seth T. Rittenhouse** [4], **Manfred J. Mark**[1,2], **Francesca Ferlaino**[1,2]

[1] *Universität Innsbruck, Fakultät für Mathematik, Informatik und Physik, Institut für Experimentalphysik, 6020 Innsbruck, Austriar*
[2] *Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, 6020, Innsbruck, Austria*
[3] *Department of Physics and Astronomy, Trinity University, San Antonio, Texas 78212, USA*
[4] *Department of Physics, the United States Naval Academy, Annapolis, Maryland 21402, USA*

Lanthanides, such as erbium and dysprosium, have emerged as valuable resources in quantum-gas science [**1**]. Among many interesting properties, like their strong magnetic dipole-dipole interactions and their rich optical spectrum, they are known for their large spin manifold in the ground state. To utilize these characteristics, precise control of the spin population and a thorough understanding of the underlying collision processes is needed.

Here, we demonstrate a novel method for manipulating the spin population in bosonic erbium by using a laser tuned to a clock-like transition present in erbium at 1299nm [**2**, **3**]. By applying a sequence of Rabi-pulse pairs we can climb the ladder of Zeeman sublevels and prepare arbitrary superpositions of spin states. This allows us to record Feshbach resonance spectra of various spin mixtures to investigate spin-dependent scattering processes. We observe a series of Fano-shaped resonances in the atom number spectra, showing regions where inelastic collisions are reduced by an order of magnitude. We interpret this from interferences between different inelastic pathways. We model our system with a multi-channel square-well model and find good agreement with the experimental data. These results pave the way for the implementation of advanced lattice spin models.

References

[1] Norcia, M.A., Ferlaino, F. *Developments in atomic control using ultracold magnetic lanthanides.* Nat. Phys. **17**, 1349–1357 (2021).

[2] A. Patscheider, et. al. Phys. Rev. Research **3**, 033256 (2021).

[3] F. Claude, et. al. Phys. Rev. Research **6**, L042016 (2024).

A single emitter emitting resonance fluorescence into a coherent probe beam

T. Lamich[1], **L. Zarraoa**[1], **R. Veyron**[1], **M. W. Mitchell**[1,2]

[1]*ICFO - Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain*
[2]*ICREA - Institució Catalana de Recerca i Estudis Avançats, 08010 Barcelona, Spain*

Resonance fluorescence from a single emitter is a paradigmatic quantum light source, in which a two-level system is coherently driven by laser light, and in response emits light that is anti-bunched, squeezed, and entangled. In 2021, Goncalves et al. [1] studied a variant of resonance fluorescence, in which the driven single emitter is placed in a probe beam containing a weak coherent state, a scenario that allows for both interference of laser light against resonance fluorescence, and stimulated emission by a single emitter.

We present an experimental implementation of the Goncalves et al. scheme, focussing on the exotic non-classical correlations produced in this way. A number of interesting and potentially useful features are predicted by Goncalves et al., including (under different conditions of pump-probe relative phase and power) the complete extinction of the probe, amplification of the probe and generation of extremes of antibunching and bunching, i.e., $g^{(2)}$ approaching zero or infinity. The predictions for transmitted power and $g^{(2)}$ can be given in terms of a single parameter, an effective coupling efficiency suggesting that interference can be used to make up for geometrical and technical limitations on the coupling to single atoms.

We use a single atom far-off-resonance trap in a "Maltese cros" geometry of four high numerical aperture lenses [2] to realise the interaction between a ^{87}Rb atom, a strong pump beam, and a weak probe beam as described in the proposed scheme [1]. We will present a scheme for using the transmission measurement not only to show the interference effects but also to sort individual atoms based on the relative pump-probe phase at the moment of measurement, thus achieving the post-measurement phase stabilisation necessary for the $g^{(2)}$ measurements.

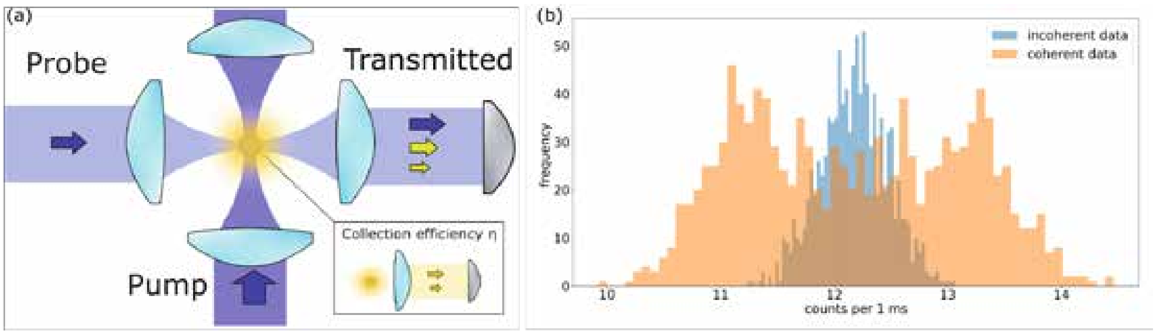


FIG. 1: (a) A strong pump beam excites a single atom acting as a single two-level emitter, while a weaker probe beam is also focused on the atom [1]. (b) Observation of phase-sensitive $g^{(1)}$ correlations in the transmitted probe beam. The blue histogram shows collected photons per millisecond averaged over the pump-probe phase, and the orange histogram shows the same with a nearly constant phase. The resulting arcsine-like distribution makes evident the interference of laser and resonance fluorescence light.

References

[1] D. Goncalves, M. W. Mitchell, et al. *"Unconventional quantum correlations of light emitted by a single atom in free space"*. In: Phys. Rev. A 104 (1 2021), p. 013724. doi:10.1103/PhysRevA.104.013724.

[2] L. C. Bianchet, N. Alves, et al. *"Manipulating and measuring single atoms in the Maltese cross geometry"*. In: Open Research Europe 1.102 (2022). doi: 10.12688/openreseurope.13972.2.

Unmasking the Polygamous Nature of Quantum Nonlocality

P. Cieśliński[1], L. Knips[2,3,4], M. Kowalczyk[1], W. Laskowski[1], T. Paterek[1,5], T. Vértesi[6], H. Weinfurter[1,2,3,4]

[1] *Institute of Theoretical Physics and Astrophysics, University of Gdańsk, 80-308 Gdańsk, Poland*
[2] *Max Planck Institute for Quantum Optics, 85748 Garching, Germany*
[3] *Faculty of Physics, Ludwig Maximilian University, 80799 Munich, Germany*
[4] *Munich Center for Quantum Science and Technology, 80799 Munich, Germany*
[5] *School of Mathematics and Physics, Xiamen University Malaysia, 43900 Sepang, Malaysia*
[6] *Institute for Nuclear Research, 4001 Debrecen, Hungary*

Quantum nonlocality is one of the most intriguing features of quantum theory. Beginning with the famous EPR argument [1], continuing through the pioneering works of John Bell [2], and extending to various experiments [3-6], it reveals the impossibility of a local-realistic description of quantum phenomena. The violation of a Bell inequality now serves not only as a fundamental test of statements about the nature of reality but also finds applications in many areas of modern quantum technologies. One crucial concept in the study of quantum nonlocality is the monogamy principle, which states that it is impossible to simultaneously violate all k-partite ($k < N$) two-setting Bell inequalities among N different parties.

Following the early findings by Scarani and Gisin [7], and later by Toner and Verstraete [8-9], this principle became a fundamental result in the field. For three parties (A, B, C), Bell monogamy is well established: if one pair of observers (A, B) violates the CHSH inequality, simultaneous violation by the pair (B, C) is impossible. This result is commonly referred to as monogamy.

However, as shown in this work, the monogamy principle is not a fundamental law. Instead, it is merely a consequence of the specific mathematical structure of certain inequalities, which are not universal. To support this claim, we develop a systematic method for constructing Bell inequalities among $N-1$ observers that do not obey to the monogamy principle for all $N > 3$. Using permutation symmetry, we find that for $N \geq 5$, Mermin inequalities [10] can be simultaneously violated across all $(N-1)$-qubit subsystems, with the effect increasing exponentially with N. Even for $N = 4$, we identify a three-qubit inequality that allows for simultaneous violation in all three-party subsystems. Furthermore, we present an intriguing minimalistic polygamous scenario, based solely on bipartite correlations between all pairs of observers. We show that the simultaneous violation of all inequalities is possible when the number of parties is $N = 18$.

Recognizing the practical challenges associated with generating high-fidelity quantum states in experimental setups, we identify inequalities that are violated experimentally by noisy six-qubit Dicke states [11-12]. Thus, the polygamous nature of quantum nonlocality is both theoretically proven and experimentally confirmed. For the full manuscript, see [13].

References

[1] A. Einstein, B. Podolsky, and N. Rosen, *Phys. Rev.* 47, 777 (1935)

[2] J. S. Bell, *Phys. Phys. Fiz.* 1, 195 (1964)

[3] A. Aspect, J. Dalibard, and G. Roger, *Phys. Rev. Lett.* 49, 1804 (1982)

[4] B. Hensen, et al., *Nature* 526, 682 (2015)

[5] M. Giustina, et al. *Phys. Rev. Lett.* 115, 25 (2015)

[6] W. Rosenfeld, et. al., *Phys. Rev. Lett.* 119, 1 (2017)

[7] V. Scarani and N. Gisin, *Phys. Rev. Lett.* 87, 117901 (2001)

[8] B. Toner, F. Verstraete, preprint at https://arxiv.org/abs/quant-ph/0611001 (2006)

[9] B. Toner, *Proc.R.Soc.A* 465, 59 (2009)

[10] N. D. Mermin, *Phys. Rev. Lett.* 65, 1838 (1991)

[11] W. Wieczorek, et. al., *Phys. Rev. Lett.* 103, 020504 (2009)

[12] R. Krischek, et. al. *Nat. Photonics* 4, 170 (2010)

[13] P. Cieśliński, et. al., PNAS 121, e2404455121 (2024)

Parametric amplification for witnessing non-classicality and non-Gaussianity

Mahmoud Kalash[1,2], M.H.M. Passos [1], Éva Rácz[3], László Ruppert[3], Radim Filip[3], and Maria V. Chekhova[1,2]

[1] *Max Planck Institute for the Science of Light, Staudtstraße 2, 91058 Erlangen, Germany*
[2] *Friedrich-Alexander Universität Erlangen-Nürnberg, Staudtstraße 7/B2, 91058 Erlangen, Germany*
[3] *Department of Optics, Palacký University, 17. listopadu 1192/12, 779 00 Olomouc, Czech Republic*

A phase-sensitive optical parametric amplifier (OPA) is well known as a *noiseless amplifier*, i.e, it amplifies an input state without adding extra noise. Recently, an OPA followed by direct detection has been employed to map quadratures onto photon numbers, enabling squeezing measurements [**1**] and Wigner function tomography [**2**].

In this work, we propose an OPA to witness the non-Gaussianity and non-classicality of distinct quantum states. It is done by directly measuring the mean photon number and the second-order correlation function of the quantum states that we are interested in after its phase-sensitive parametric amplification. Figure 1 (a) illustrates our experimental proposal based on seeding an OPA with a heralded single-mode quasi-single-photon state and monitoring its non-Gaussainity while increasing its brightness. On the other side, to reinforce the validity and robustness of our results, we also compare our findings with the standard model to witness the non-Gaussianity based on the three-fold coincidence measurements [**3**], shown in Fig.1 (b). Fig. (c) illustrates the results obtained by our proposal. It is worth mentioning that another strong fundamental advantage of applying OPAs for such a proposal is their ability to perform multimode amplification, enabling the simultaneous certification of non-Gaussianity in multiple modes occupied by different states. This capability is pivotal for the advancement of quantum technologies.

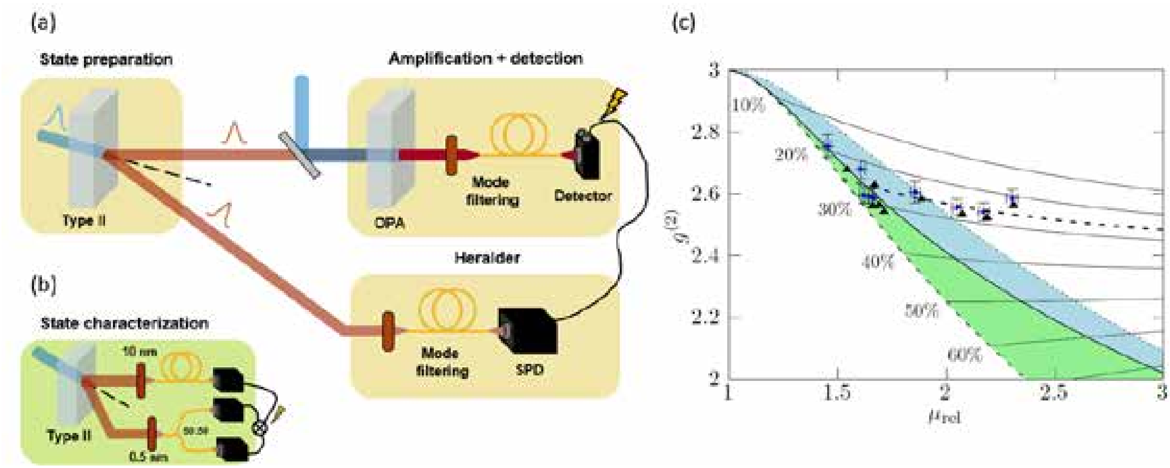


Figure 1: Experimental setup and results for witnessing non-Gaussianity and non-classicality via parametric amplification. (a) State preparation and amplification via an OPA. (b) State characterization via a heralded detection scheme. (c) Measured $g^{(2)}(0)$ as a function of the relative mean photon number $\mu_{\rm rel}$, with theoretical predictions for different amplification efficiencies (solid horizontal lines). The green-shaded region denotes the non-Gaussian regime, while the blue-shaded region indicates the non-classical regime.

References

[1] Y. Shaked, Y. Michael, R. Z. Vered, L. Bello, M. Rosenbluh, and A. Pe'er, Nat. Commun. **9**, 1–12 (2018).

[2] M. Kalash and M. V. Chekhova, Optica **10**, 1142–1146 (2023).

[3] M. Ježek, I. Straka, M. Mičuda, M. Dušek, J. Fiurášek, and R. Filip, Phys. Rev. Lett. **107**, 21 213602 (2011).

Interference of Photons from Independent Hot Atoms

J. Mika[1], **S. Joshi**[1], **R. Kaiser**[2], **L. Slodička**[1]

[1] *Department of Optics, Palacký University, 17. listopadu 12, 771 46 Olomouc, Czech Republic*
[2] *Université Côte d'Azur, CNRS, INPHYNI, 17 Rue Julien Lauprête, 06200 Nice, France*

The feasibility of coherence of light from atomic ensembles is paramount in quantum optics. We propose and experimentally demonstrate an interferometric scheme that provides observability of the mutual coherence of light scattered from independent ensembles of hot atoms. The random phase fluctuations of the scattered light caused by a large thermal motion and Doppler broadening prevent direct observability of phase coherence. However, as originally proposed in the seminal work by L. Mandel, the stable frequency difference between scattered photons can provide observability of a strong periodic modulation due to the photon interference in the temporal second order correlation function $g^{(2)}(\tau)$. We demonstrate the corresponding interference phenomena for the first time with independent atomic light sources.

The simplified scheme for observation of interference of light from warm atomic vapors is displayed in Figure 1 a). It depicts the elementary case of excitation of ensembles of two-level atoms by counterpropagating lasers with frequency ω_{L}, detuned by Δ from the atomic transition ω_{A}. These lasers scatter off the statistically independent classes of atoms given by their respective Doppler shifts along their propagation direction. In the forward scattering, the corresponding Doppler shift effectively compensates and photon frequency remains unchanged up to the residual Doppler broadening with a linewidth σ_{D}, given by the scattering angle θ. The retroreflected laser scatters on atoms with opposite directions of motion but with the same velocity magnitude. The corresponding backward-scattered photons are frequency-shifted by $\approx \Delta$ with respect to an observer in the frame moving with the atomic scatterer and by $\approx 2\Delta$ to the forward-scattered photons. The photons are collected in the same optical mode and measurement of the second-order correlations $g^{(2)}(\tau)$ provides observable coherent frequency beating with a period of $1/(2\Delta)$ (Figure b)).

The presented methodology with hot atoms has a direct application in atomic and molecular spectroscopy in the form of a precise sub-Doppler estimation of an absolute value of the relative frequency detuning between the excitation laser and internal electronic transition. In contrast to commonly employed approaches that rely on the observability of laser absorption in optically sufficiently dense atomic or molecular vapors, the presented method provides sub-Doppler spectroscopy of hot atoms even in the regime of extremely low optical depth and a few-photon level intensity of scattered light.

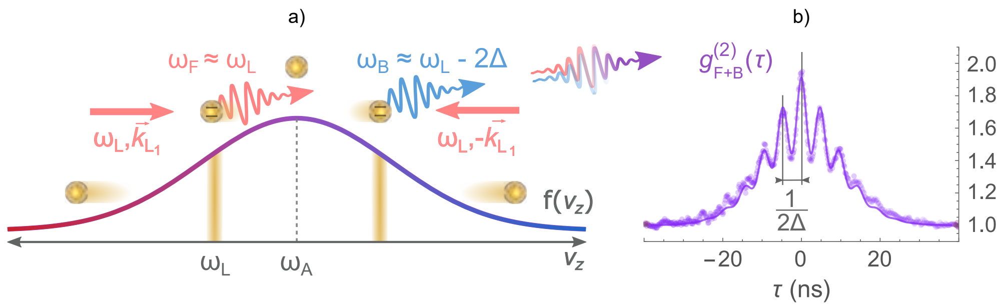


Figure 1: a) The principle of interference of light from independent warm atomic ensembles. The laser at the frequency ω_{L} scatters off the particular velocity class of atoms which follow the thermal velocity distribution $f(v)$. Indexes F and B denote forward and backward scattering, respectively. b) The example measurement of the $g^{(2)}_{\mathrm{F+B}}(\tau)$. The measurement of the second-order correlations $g^{(2)}(\tau)$ provides coherent frequency beating with a period of $1/(2\Delta)$.

References

[1] L. Mandel, Phys. Rev. **134**, (1964).

[2] J. Mika, S. Joshi, R. Kaiser, L. Slodička, arXiv:2409.18651.

Experimental noiseless quantum amplification of coherent states of light by two-photon addition and subtraction

M. Neset[1], J. Fadrný[1], M. Bielak[1], J. Fiurášek[1], M. Ježek[1], J. Bílek[1],

[1]*Department of Optics, Faculty of Science, Palacký University, 17. listopadu 12, 77900 Olomouc, Czech Republic*

Controlled addition and subtraction of single photons represent crucial tasks of quantum state engineering and fundamental building blocks of nonlinear photonic devices. Here, we report on the experimental implementation of a noiseless quantum amplifier for coherent states of light that is based on the conditional addition of two photons followed by the conditional subtraction of two photons. [1] We comprehensively characterize the noiselessly amplified coherent states via quantum state tomography and analyze the amplification gain and noise properties of the amplifier. We observe very good agreement between the experiment and theoretical predictions. We show that the performance of our noiseless amplifier is essentially the same as the performance of an interferometric scheme, where the signal is split into two modes, each mode is noiselessly amplified, and the modes are interferometrically recombined. Sequences of multiple photon additions and subtractions thus represent an efficient and experimentally feasible alternative to multiplexing that was originally proposed to boost the performance of noiseless quantum amplifiers. Beyond noiseless quantum amplification, our experiment represents a significant step forward towards engineering complex quantum operations on traveling light beams by coherent combinations of various sequences of multiphoton additions and subtractions.

References

[1] Experimental noiseless quantum amplification of coherent states of light by two-photon addition and subtraction, M. Neset, J. Fadrný, M. Bielak, J. Fiurášek, M. Ježek and J. Bílek, arXiv preprint arXiv: 2412.13342, (2024).

Towards a 1D Array of Cold Rydberg Atoms Near the Surface of an Optical Nanofibre

S. Nic Chormaic[1], A. Kortel[1], S. Abdrakhmanov[1], A. Raj[1], Z. Shahrabifarahani[1], M. Dondi[1,2], A. Vylegzhanin[1], W. Li[1], K. Jadeja[1], D. Brown[1,3]

[1]*Okinawa Institute of Science and Technology Graduate University, Okinawa 904-0495, Japan*
[2]*Department of Physics and Astronomy "Augusto Righi", University of Bologna, 40127 Bologna, Italy*
[3]*Department of Physics, Imperial College London, London SW7 2AZ, United Kingdom*

Optical nanofibres (ONF) are very thin (subwavelength size) optical fibres, usually made from commercial silica fibre via a heat-and-pull method [1]. They provide tightly confined, very intense, light fields that extend exponentially from the fibre/air interface when light is guided through them. These fields can be used to probe, trap, and manipulate particles, including atoms, that fall within the light field. Additionally, the evanescent field has a very steep gradient, which can be exploited to explore quadrupole excitations in atomic samples [2]. For a perspective paper related to the advantages and challenges of using ONFs with atoms, the reader may refer to [3]. In this work, we focus on the integration of optical nanofibres with cold ^{87}Rb atoms and discuss several current research topics including our work towards the generation of a 1D array of cold Rydberg atoms (principal quantum number, $n \sim 30$) near the nanofibre and novel trapping schemes that we are exploring for ground state and Rydberg state atoms at controlled distances from the ONF surface. These techniques are useful for Rydberg atom quantum networks.

We have already demonstrated the excitation of Rydberg atoms from a magneto-optical trap (MOT) mediated via an ONF of diameter ~ 350 nm and have shown that the excitation is limited by surface interactions when the atoms are closer than about 250 nm to the fibre surface [4,5]. We have also successfully trapped about 500 ground state atoms from the MOT into a two-colour fibre trap [6]. Here, we discuss our progress on Rydberg excitation of the dipole-trapped atoms and alternative methods that may be used for generating an ordered array of Rydberg atoms next to the ONF. For example, we are incorporating holographic atom traps, generated using a spatial light modulator, as one possible methodology. This would allow us to precisely control the number of atoms from single to multiple for observing collective effects.

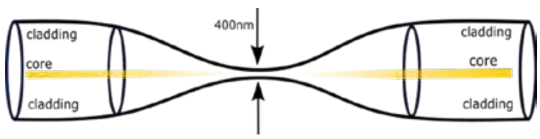


FIG. 1: Schematic of an optical nanofibre used for trapping laser-cooled atoms in a two-colour optical dipole trap. The nanofibre is the thinnest region of the fibre.

References

[1] J. M. Ward, A. Maimaiti, V. H. Le, S. Nic Chormaic, Rev. Sci. Instrum. **85**, 111501 (2014).

[2] T. Ray, R. K. Gupta, V. Gokhroo, J. L. Everett, T. Nieddu, K. S. Rajasree, S. Nic Chormaic, New J. Phys. **22**, 062001 (2020).

[3] W. Li, D. Brown, A. Vylegzhanin, Z. Shahrabifarhani, A. Raj, J. Du, S. Nic Chormaic, J. Phys.: Photon. **6**, 021001 (2024).

[4] K. S. Rajasree, T. Ray, K. Karlsson, J. L. Everett, S. Nic Chormaic, Phys. Rev. Res. **2**, 012038(R) (2020).

[5] A Vylegzhanin, D. J. Brown, A. Raj, D.F. Kornovan, J. L. Everett, E. Brion, J. Robert, S. Nic Chormaic, Optica Quant. **1**, 6 (2023).

[6] R. K. Gupta, J. L. Everett, A. D. Tranter, R. Henke, V. Gokhroo, P. K. Lam, S. Nic Chormaic, AVS Quantum Sci. **4**, 026801 (2022).

Deterministic generation of large Schrödinger cat states beyond Gaussian coupling

M. N. Notarnicola[1], M. Jarzyna[2], R. Filip[1]

[1] *Department of Optics, Palacký University, 17 Listopadu 12, 779 00 Olomouc (Czech Republic)*
[2] *Centre for Quantum Optical Technologies, Centre of New Technologies, University of Warsaw, Banacha 2c, 02-097 Warszawa (Poland)*

The generation of Schrödinger cat states on different platforms is one of the tasks in quantum information science, not only from a fundamental perspective, to highlight the transition from quantum to classical physics, but also for practical purposes, as they provide resource for quantum sensing, communication and computation. To this aim, a key role is played by optical cat states, corresponding to superpositions of coherent states with opposite phases, namely $|\psi_\pm\rangle = \mathcal{N}_\pm(|\alpha\rangle \pm |-\alpha\rangle)$, $\alpha \in \mathbb{C}$. Conventional methods to create them are based on either multiple photon subtraction from squeezed vacuum [1,2] or multiple photon addition to vacuum [3], that both exploit Gaussian coupling between the signal and an ancillary mode, followed by photon-number-resolving (PNR) detection, resulting in probabilistic schemes with limited application for large α. On the contrary, other platforms, e.g. cavity QED, have been recently demonstrated as more natural candidates [4-8].

In this work, we perform a first systematic analysis of the different protocols for cats generation, both in terms of fidelity and phase-space properties of the output states. At first, we design the ultimate Gaussian coupling (UG) protocol, that determines the best performances achievable by Gaussian protocols, obtained by optimized coupling and PNR detection [9]. In particular, we show Gaussian methods to be limited by the number of heralded photons, thus not being a proper scalable strategy for large cats generation.

In light of this, we proceed beyond Gaussian interactions, and propose deterministic protocols based on feasible examples of qubit-light interaction, namely Jaynes-Cummings (JC) and dispersive coupling, both currently available in cavity QED systems. In the JC protocol, a coherent state of radiation is coupled to a two-level system and, if the interaction time is properly tuned, light is left into a superposition of two symmetric wavepackets, resulting in a cat-like state. However, the nonlinearity of the interaction ineludibly introduces a degree of anharmonicity, that degrades the quality of the output state. On the contrary, dispersive interaction implements a conditional phase-shift, being able to create atom-light entangled state that, once the atom is measured in a proper superposition of ground and excited state, projects the light into either even or odd optical cat state. By embedding Gaussian feedforward into this scheme [10], we make the protocol deterministic and produce large cat states with large fidelity close to 1 and many oscillations in both the Wigner function and the homodyne probability distribution.

Our results show dispersive coupling as a promising tool to create superposition states in the optical domain, that could be flexibly extended to target even more exotic states of radiation, e.g. multi-headed cats.

References

[1] A. Ourjoumtsev, R. Tualle-Brouri, J. Laurat, and P. Grangier, *Science* **312**, 83–86 (2006).

[2] K. Takaseet et al., *Phys. Rev. A* **103**, 013710 (2021).

[3] Y.-R- Chen et al., *Phys. Rev. A* **110**, 023703 (2024).

[4] J. Gea-Banacloche, *Phys. Rev. A* **44**, 5913 (1991).

[5] M. Bild et al., *Science* **380**, 274–278 (2023).

[6] B. Hacker et al., *Nat. Photon.* **13**, 110–115 (2019).

[7] J. Hastrup and U. L. Andersen, *Phys. Rev. Lett.* **128**, 170503 (2022).

[8] G. P. Teja and Chanchal, *Phys. Rev. Applied* **20**, 044049 (2023).

[9] M. N. Notarnicola, M. Jarzyna, and R. Filip, *in preparation.*

[10] M. N. Notarnicola, *Int. J. Quantum Inf.* **23**, 2550003 (2025).

Interaction between atoms and light: the ultimate bounds to precision for atomic clock frequency measurement

S. Olivares[1], S. Micalizio[2], M. G. A. Paris[1]

[1] *Department of Physics "Aldo Pontremoli", University of Milan and INFN Sezione di Milano (Italy)*
[2] *INRIM, Quantum Metrology and Nanotechnologies Division, Turin (Italy)*

Measuring the atomic clock frequency has fundamental and practical relevance. Here, we investigate the ultimate quantum limits to the achievable uncertainty in the estimation of the transition frequency between two atomic levels.

Among the possible measurement techniques, we consider the Rabi, the Ramsey, and the coherent population trapping (CPT) schemes (Fig. 1), which are widely employed in experiments and in technological applications. We theoretically prove that the estimation strategy based on the considered techniques allows one to achieve the ultimate limits to precision imposed by quantum mechanics. Our approach, based on estimation and quantum estimation theory, leads us to prove that the Ramsey method beats both the Rabi and the CPT performance, as also suggested by the results of current experiments. As a figure of merit, we consider the Fisher information of the atomic population measurement and compare its value to the quantum Fisher information, corresponding to the maximum precision optimized over all the possible feasible measurements.

Interestingly, when a measurement involving the coherences between the levels is considered, we find that for the CPT the Fisher and the quantum Fisher information are only slightly different for any value of the detuning between the atomic frequency and the probe one and they coincide at resonance. However, for the Rabi and Ramsey methods, the quantum Fisher information is sensibly higher than the classical one for nonzero values of the detuning, thus fostering new investigation for different detection schemes allowing one to reach that limit.

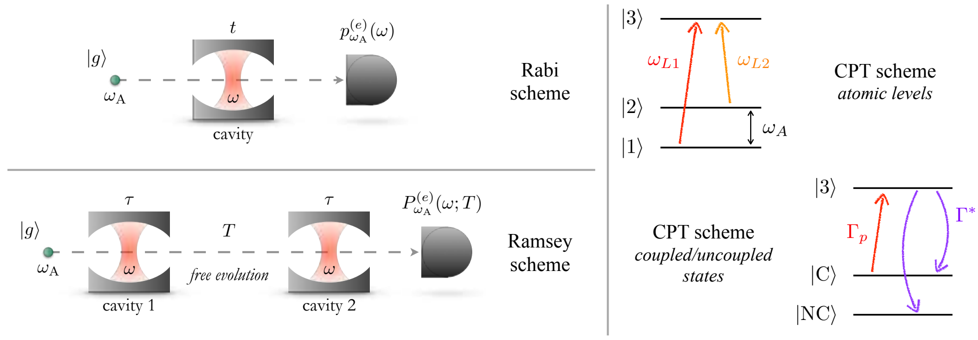


FIG. 1: Sketch of the considered measurement techniques: Rabi, Ramsey, and coherent population trapping (CPT) schemes (adapted from Ref. [1]).

References

[1] S. Olivares, S. Micalizio and M. G. A. Paris, *The ultimate bounds to precision of atomic clock frequency measurement techniques*, preprint arXiv:2501.17693 (2005).

Abstract submission for CEWQO29
Building a neutral atoms platform for the study of collective light-matter interactions

S. Pancaldi[1], ***A. Gavalda***[2], ***G. Tremblier***[1], ***I. Ferrier-Barbut***[1], ***A. Browaeys***[1]

[1] *Laboratoires Charles Fabry, Institut d'Optique, Université Paris Saclay, France*
[2] *PASQAL, France*

Our set-up consisting of a cloud of laser-cooled rubidium atoms trapped in optical tweezers has allowed us to explore collective light-matter interaction phenomena predicted by Dicke [1] such as *subradiance* and *superradiance*, [2]. The key characteristic of this set-up is the capability of trapping thousands of atoms in the same optical tweezers, whose radial dimension is smaller than the excitation wavelength of rubidium. More recently, we investigated how these spontaneous atomic correlations affect the statistics of the light emitted by the cloud [3].
We are currently in the process of building a newer version of our set-up, including a glass cell to provide more optical access to the atomic medium and flexibility to change trapping and detection paths. We hope this updated version will also be able to scale up the number of atoms we can trap, allowing us to explore denser regimes.

[1] R. H. Dicke, *Coherence in spontaneous radiation processes* Phys. Rev. **93.1** (1954) : 99.

[2] A. Glicenstein, G. Ferioli, A. Browaeys, and I. Ferrier-Barbut *From superradiance to subradiance: exploring the many-body Dicke ladder*, Optics Letters **47**, 1542 (2022).

[3] G. Ferioli, S. Pancaldi, A. Glicenstein, D. Clement, A. Browaeys, I. Ferrier-Barbut *Non-Gaussian correlations in the steady-state of driven-dissipative clouds of two-level atoms*, Phys. Rev. Lett. **132**, 133601 (2024)

Enabling Hybrid Quantum Networks: Protocols and Experimental Progress Toward Memory-Compatible Links

M. Pasini[1], **N. Rego**[1], **F. Hoffet**[1], **L. Schumacher**[1], **H. de Riedmatten**[1,2]

[1]*ICFO – Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, Castelldefels (Barcelona) 08860, Spain*
[2]*ICREA – Institucio Catalana de Recerca i Estudis Avançats, 08015 Barcelona, Spain*

Connecting quantum computers and systems into a network is a critical milestone for unlocking transformative applications — from distributed quantum computing and entanglement-based secure communication to enhanced sensing. Different physical platforms, including cold atoms and solid-state systems, have emerged as optimal solutions for specific network tasks, such as processing nodes or quantum memories. For this reason, hybrid architectures and protocols that allow connecting diverse quantum systems are crucial tools for building a large-scale, functional quantum network that can leverage the full potential of quantum technologies.

A key challenge in quantum networking is generating long-distance entanglement, which is limited by photon loss in direct transmission. Quantum repeaters, leveraging multiplexed memory nodes and entangled photon sources, offer a solution. Solid-state rare-earth ion-based quantum memories stand out as a mature platform for this task, as evidenced by recent breakthroughs in memory-memory entanglement. Yet, a functional quantum link between such a memory node and a quantum processing unit remains an open challenge.

In this work, I will first present a theoretical framework for designing entanglement protocols across heterogeneous hardware platforms. Then, I will introduce a blueprint for a prototype hybrid quantum network link, combining a rudimentary cold-atom processing node with a rare-earth ion-based solid-state quantum memory. I will share the latest experimental progress toward realizing entanglement between these systems and explore use cases in quantum information processing.

Femtosecond laser-based creation of single-photon sources in hBN for quantum communications applications

T. Paulauskas,[1] E. Markauskas,[1] M. Maciaszek,[2] L. Razinkovas,[1] J. Janušonis,[1] D. Rutkauskas,[1] V. Gulbinas[1]

[1]*Center for Physical Sciences and Technology, Vilnius, Lithuania*
[2]*Warsaw University of Technology, Warsaw, Poland*

Quantum key distribution (QKD) networks will be essential for ensuring secure communications in critical infrastructure, given the rapidly advancing capabilities of quantum computing. True single-photon sources are essential QKD components and are generally preferable to attenuated coherent light sources. In this talk, we present the site-selective creation of atomic defect–based single-photon sources in hexagonal boron nitride (hBN) using a femtosecond pulsed laser. The laser-written single-photon sources emit in the visible to near-infrared range and exhibit high brightness and stability at room temperature. Atomic configurations of the resulting defects are investigated in this study through spectroscopic measurements, atomic-structural imaging, optically detected magnetic resonance, and first-principles calculations to advance the reproducible creation of these photon sources.

References

[1] Maciaszek, M.; Razinkovas, L. Blue Quantum Emitter in Hexagonal Boron Nitride and a Carbon Chain Tetramer: a First-Principles Study. ACS Appl. Nano Mater. 2024, 7 (16), 18979–18985. DOI: 10.1021/acsanm.4c02722.

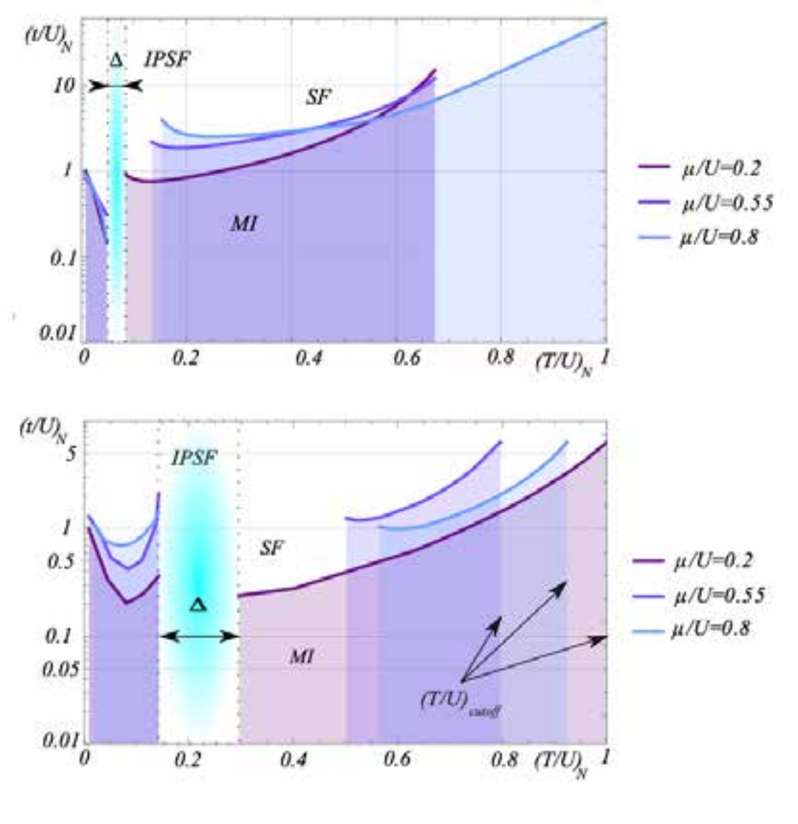
[2] Turiansky, M. E.; Alkauskas, A.; Van de Walle, C. G. Spinning up Quantum Defects in 2D Materials. Nat. Mater. 2020, 19, 487–489. DOI: 10.1038/s41563-020-0668-x.

Interaction-based and imaginary time-based bosonic pairing mechanisms

T. P Polak[1],

Institute of Spintronics and Quantum Information,
Faculty of Physics, Adam Mickiewicz University in Poznań, Poland.

We compare two kinds of bosonic pairing, with two different sources: second order terms in the series expansion of the correlation function and the density-induced tunnelling interaction. Both types of pair condensate strengthen the single condensate phase, increasing the critical temperature of bosonic condensation. Since they stem from two different mechanisms but can conceal each other we prepare protocol to distinguish between them. We apply the self-consistent harmonic approximation to the quantum phase model with single and pair condensation terms to study the thermodynamics of both kinds of pairing and add synthetic magnetic fields into the systems to look for possible ways to differentiate between the two kinds of pair condensate in experiments.



Comparison of the dependence of normalized single hopping on the normalized density induced term.

References

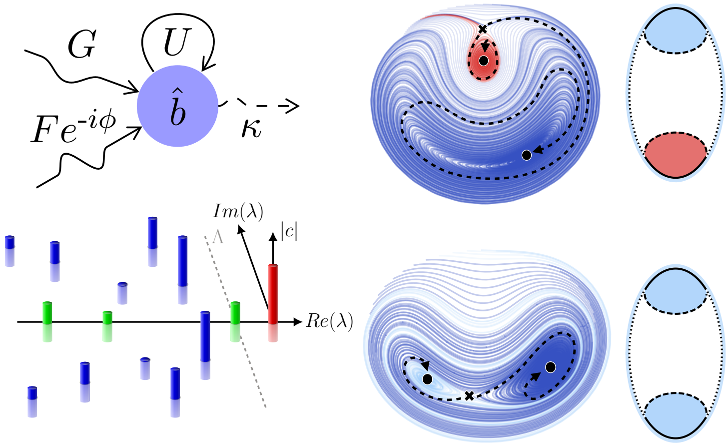
[1] Krzywicka, A., Polak, T.P. Reentrant phase behaviour in systems with density-induced tunnelling. *Sci Rep* **14**, 10364 (2024).

[2] Krzywicka, A. & Polak, T. Coexistence of two kinds of superfluidity at finite temperatures in optical lattices. *Ann. Phys.* **443**, 168973 (2023).

Quantum Morse-Smale topology for Kerr-Cat qubits

Kilian Seibold,[1] Greta Villa,[1] Javier del Pino,[1,2] and Oded Zilberberg[1]
[1]*Department of Physics, University of Konstanz, 78464 Konstanz, Germany*
[2]*Departamento de Física Teórica de la Materia Condensada and Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, E28049 Madrid, Spain*

We bring the classical nonlinear vector flow topology to the quantum realm. Using the master equation description and unraveling the density matrix via quantum trajectories, we demonstrate that these topological features persist in the quantum regime. In my talk, I will show how dynamical topology reveals fundamental differences between unraveled and averaged descriptions, uncovering the topological origin of phase transitions—even without Liouvillian gap closure. Moreover, I highlight the interplay between topological properties and multiphoton resonances, a purely quantum effect with no classical analog. This work bridges classical and quantum perspectives, paving the way for realizing many-body topological phases in quantum simulators.



[1] K. Seibold, G. Villa, J. del Pino, and O. Zilberberg, *In preparation*.
[2] K. Seibold, O. Ameye, and O. Zilberberg, Phys. Rev. Lett. **134**, 060401 (2025).
[3] G. Villa, J. del Pino, V. Dumont, G. Rastelli, M. Michałek, A. Eichler, and O. Zilberberg, arXiv e-prints , arXiv:2406.16591 (2024).

Measuring the Earth's rotation with entangled photons

Raffaele Silvestri

University of Vienna, Austria

Entangled quantum states offer unique advantages for precision interferometry, yet their inherent fragility poses a significant challenge when scaling up to the large interferometric areas required to detect extremely small physical effects, such as those arising from gravity. While optical quantum interferometers benefit from well-established techniques for generating and controlling quantum light, extending these capabilities to macroscopic scales has remained largely unexplored due to the difficulty of preserving entanglement over long interferometric paths. In this work, we demonstrated the controlled use of two maximally path-entangled photons in a table-top interferometer with an effective area of 715 m^2. This enabled for the first time the observation of the rotational effect of Earth on entangled photons. Our results establishes a concrete pathway toward bringing entangled quantum states of light into new sensitivity regimes where gravitational effects do matter.

Visualizing Quantum Dynamics in Phase Space using Wigner's Current

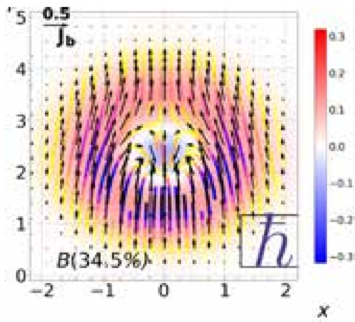
Ole Steuernagel

Institute of Photonics Technologies, National Tsing Hua University, Hsinchu 30013, Taiwan

When Jose Moyal tried to publish his work on quantum dynamics [2] in phase space, using Wigner's phase space distribution, he was stopped by Paul Dirac, for years. Dirac struggled to understand Moyal's approach.

Confusion about quantum dynamics in phase space still exists today [3]. In my talk I will introduce Wigner's phase space current that governs the dynamics of the Wigner distribution.

I will describe squeezing [1], using the perspective of Moyal's equation and Wigner's current, as well as beam splitters [4] and more complicated systems.



Wigner Current for the mixing of a single photon Fock state with a weak coherent state [4]. The phase space dynamics is nonclassical. Phase space volumes are not conserved and trajectories do not exist [3].

[1] Chen, Y.-R., Hsieh, H.-Y., Ning, J., Wu, H.-C., Chen, H. L., Chuang, Y.-L., Yang, P., Steuernagel, O., Wu, C.-M., and Lee, R.-K. Experimental reconstruction of wigner phase-space current. *Phys. Rev. A 108* (2023), 023729.

[2] Moyal, J. E. Quantum mechanics as a statistical theory. *Proc. Cambridge Philos. Soc. 45* (1949), 99.

[3] Oliva, M., Kakofengitis, D., and Steuernagel, O. Anharmonic quantum mechanical systems do not feature phase space trajectories. *Physica A 502* (2018), 201–210.

[4] Steuernagel, O., and Lee, R.-K. Wigner's phase space current for variable beam splitters—seeing beam splitters in a new light. *J. Opt. Soc. Am. B 42*, 2 (Feb 2025), 194–200.

Adressing Challenges in Near-Infrared Squeezed Light Generation: Absorption Effects and Phase Stabilization

Santiago Tabares[1], **Diana Mendez**[1], **Aleksandra Sierant**[1] **and Morgan W. Mitchell**[1,2]

[1] *ICFO - Institut de Ciències Fotòniques, The Barcelona Institute of Science and Technology, Castelldefels (Barcelona) 08860, Spain*
[2] *ICREA - Institució Catalana de Recerca i Estudis Avançats, Barcelona 08010, Spain*

A light squeezer is an optical system that exploits Heisenberg's uncertainty principle, reducing quantum noise in one quadrature of the electromagnetic field at the expense of increased noise in the conjugate quadrature. Common implementations of light squeezers include optical parametric oscillators (OPOs), where a nonlinear crystal inside a resonator mixes two beams (pump and signal), converting energy from the pump wavelength to the wavelength of interest in a process known as parametric down-conversion. Typically, the higher the pump power, the greater the squeezing achieved, with squeeze factors reaching values between 13 and 15 dB [1, 2]. However, when the wavelength of interest lies close near-infrared spectrum, the pump (whose wavelength lies near blue spectrum) induces absorption of the signal beam by the crystal, converting optical power into heat in a process known as Blue Light Induced InfraRed Absorption (BLIIRA)[3].
Here we present an initial design of our new light-squeezer at the Rubidium D1 transition-resonant wavelength, based on the design proposed by [4], with a primary focus on the OPO design. The detrimental effects of BLIIRA will be explained, along with the choice of a proper crystal to mitigate it. Additionally, a dual coherent locking technique to lock the phases of the pump and a local oscillator -similar to that found in [5]- will also be described.

The project that led to these results received the support of a fellowship from Fundación Ramón Areces.

[1] A. Schönbeck, F. Thies, and R. Schnabel, "13 db squeezed vacuum states at 1550nm from 12mw external pump power at 775 nm," *Opt. Lett.*, vol. 43, pp. 110–113, Jan 2018.

[2] H. Vahlbruch, M. Mehmet, K. Danzmann, and R. Schnabel, "Detection of 15 db squeezed states of light and their application for the absolute calibration of photoelectric quantum efficiency," *Physical Review Letters*, vol. 117, Sept. 2016.

[3] S. Tjörnhammar, V. Maestroni, A. Zukauskas, T. K. Uždavinys, C. Canalias, F. Laurell, and V. Pasiskevicius, "Infrared absorption in ktp isomorphs induced with blue picosecond pulses," *Opt. Mater. Express*, vol. 5, pp. 2951–2963, Dec 2015.

[4] A. Predojević, Z. Zhai, J. M. Caballero, and M. W. Mitchell, "Rubidium resonant squeezed light from a diode-pumped optical-parametric oscillator," *Phys. Rev. A*, vol. 78, p. 063820, Dec 2008.

[5] A. Schönbeck, *Compact squeezed-light source at 1550 nm.* PhD thesis, 2018.

Bosonic error mitigation and suppression with linear optics

Y. S. Teo[1], S. U. Shringarpure[1], S. Cho[1], and H. Jeong[1]

[1] *NextQuantum and Department of Physics & Astronomy, Seoul National University, South Korea*

Bosonic modes, though promising candidates for quantum computation, are susceptible to noise. In our latest preprint [1], we propose linear-optical schemes to mitigate bosonic thermal and displacement noise, and suppress bosonic dephasing noise. With photon subtraction, linear attenuation/amplification and constrained statistics, thermal/displacement error cancellation (PSG-PEC) is proven (FIG. 1).

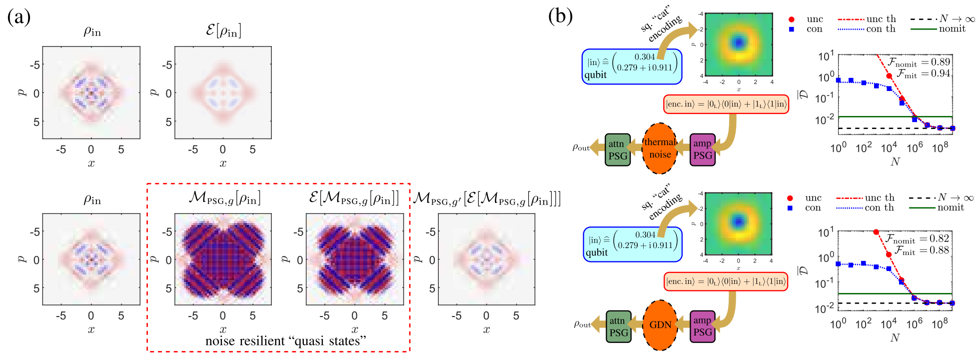


FIG. 1: (a) PSG-PEC works by fortifying interference features (4-component "cat" state). (b) This fortification is implemented with PEC to mitigate thermal and Gaussian displacement noise (GDN).

With linear optics, vacuum measurements (the vacuum Mach–Zehnder or VMZ) and linear amplification, we prove that *arbitrary* dephasing noise is invertible using infinitely-large interferometers at nonvanishing success rates. No high-order nonlinearities such as Kerr's effect are needed as presumed. Finite-size interferometric suppression is also proven to be possible for weak *Gaussian*-dephasing strength (FIG. 2).

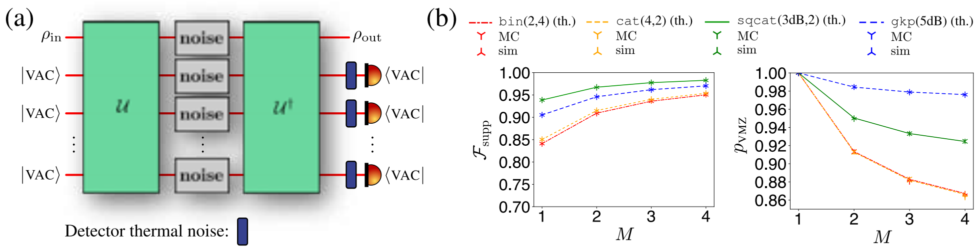


FIG. 2: (a) Large Hadamard/Haar linear-optical schemes suppress *any* dephasing noise with nonvanishing success rates. (b) Finite interferometers significantly suppress Gaussian dephasing noise.

Not only did we show mitigation and suppression for both idling and gate noise, compatibility (commutativity) between PSG-PEC and VMZ permits the mitigation of composite noise channels (FIG. 3).

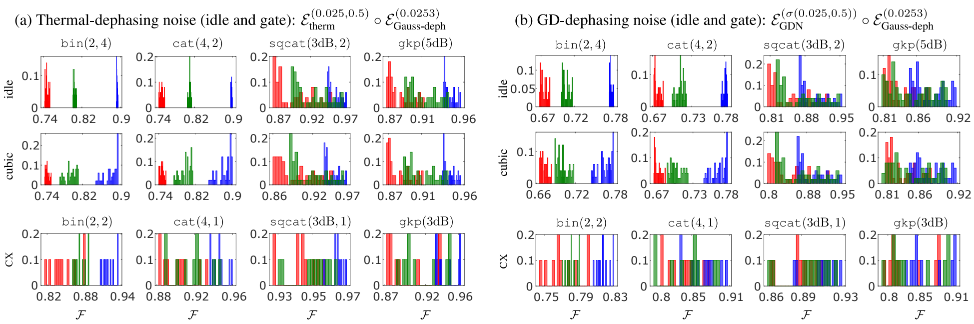


FIG. 3: Composite-noise mitigation (red: noisy; blue: perfect mitigation; green: noisy mitigation).

References

[1] Y. S. Teo, S. U. Shringarpure, S. Cho, and H. Jeong, eprint arXiv:2411.11313 (2024).

Quantum optimal precision by inner-variable resolving two-photon correlations

D. Triggiani[1,2], **V. Tamma**[3,4], **F. Di Lena**[5], **F. Sgobba**[5], **L. Santamaria**[5], **C. Lupo**[1,2]

[1] *Dipartimento di Fisica, Politecnico di Bari, Bari 70126, Italy*
[2] *INFN, Sezione di Bari, Bari 70126, Italy*
[3] *School of Mathematics and Physics, University of Portsmouth, Portsmouth PO1 3HF, UK*
[4] *Institute of Cosmology and Gravitation, University of Portsmouth, Portsmouth PO1 3FX, UK*
[5] *Agenzia Spaziale Italiana, Matera Space Center, Contrada Terlecchia snc., Matera 75100, Italy*

Two-photon interference plays an important role in modern high-precision measurement techniques. As the second-order correlations between two photons impinging on the two faces of a beam-splitter are highly sensitive to the differences between the photons, and are not affected by changes in their relative phases, these techniques are routinely employed for the measurement of differences in the values of given photonic parameters, such as colours, arrival times, polarisations, and transversal positions. However, despite recent advances, these techniques are still fundamentally hindered by the distinguishability of the photons at the detectors caused by the difference in the physical parameters we wish to estimate: the less the wavepackets of the two photons overlap, the more the photons become distinguishable at the detectors, the less visible is their interference, and thus the less sensitive is the technique.

Here, we present a two-photon interference approach based on inner-variable resolved correlation measurements that overcomes the limitation of overlapping wavepackets. In particular, we show with Fisher information analysis that this approach achieves the quantum optimal precision, that is independent on the overlap between their wavepackets. We will show that the origin of such a quantum advantage resides in the observation of beating oscillations that are normally averaged out when performing a standard two-photon coincidence experiment. We discuss and experimentally show how such an approach can be applied to disparate domains, e.g. estimation of time delays [1, 2], transverse separations [3, 4], multi-parameter polarization sensing [5], and sub-Rayleigh imaging [6], finding applications in bio-imaging, nano-imaging, single-molecule localization microscopy and exoplanet localization.

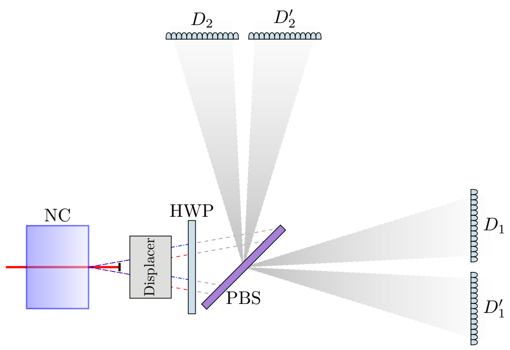


FIG. 1: Example of application of inner-variable resolving two-photon correlations that employs polarization-entangled type-2 SPDC photons and single-photon cameras for measuring with quantum optimal precision the transverse displacement between the photons [4].

References

[1] D. Triggiani et al. Phys. Rev. Applied **19**, 044068 (2023).

[2] F. Di Lena et al., to be submitted.

[3] D. Triggiani and V. Tamma, Phys. Rev. Lett. **132**, 180802 (2024).

[4] D. Triggiani and V. Tamma, Phys. Rev. A **111**, 032605 (2025).

[5] L. Maggio et al., Phys. Scr. **100**, 035106 (2025).

[6] S. Muratore et al., arXiv:2412.10057 (2024).

Engineering interactions by collective coupling of atom pairs to cavity photons for entanglement generation

Sankalp Sharma[1], **Jan Chwedeńczuk**[2], **Tomasz Wasak**[1]

[1] *Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, Grudziądzka 5, 87-100 Toruń, Poland*
[2] *Faculty of Physics, University of Warsaw, ul. Pasteura 5, PL–02–093 Warszawa, Poland*

Engineering atom-atom interactions is essential both for controlling novel phases of matter and for efficient preparation of many-body entangled states, which are key resources in quantum communication, computation, and metrology. In our work [3], we propose a scheme to tailor these interactions by coupling driven atom pairs to optical cavity photons via a molecular state in the dispersive regime, resulting in an effective potential. Such a coupling has been recently demonstrated in [1, 2], where observation of universal pair-polaritons as well as the coupling of charge and pair-density waves were reported.

As an illustrative example of our approach, we investigate two-mode ultracold bosons in an optical cavity, see Fig. 1, and by analyzing the quantum Fisher information, we show that the induced interactions can generate robust many-body entanglement. By tuning the photon-induced interactions through the cavity drive, we identify conditions for preparing highly entangled states on timescales that mitigate decoherence due to photon loss. Our results show that the entanglement formation rate scales strongly with both photon and atom number, dramatically reducing the timescale compared to bare atomic interactions. We also identify an optimal measurement for exploiting the metrological potential of the atomic state in an interferometric protocol with significant photon losses, saturating the quantum Cramer-Rao lower bound. Furthermore, we show that despite these losses the atomic state exhibits strong Bell correlations. Our results provide insights on induced atom-atom interactions and open paths to study novel phases of light and matter in hybrid atom-photon systems, as well as for tailoring complex quantum states for new quantum technology protocols and fundamental tests of quantum mechanics.

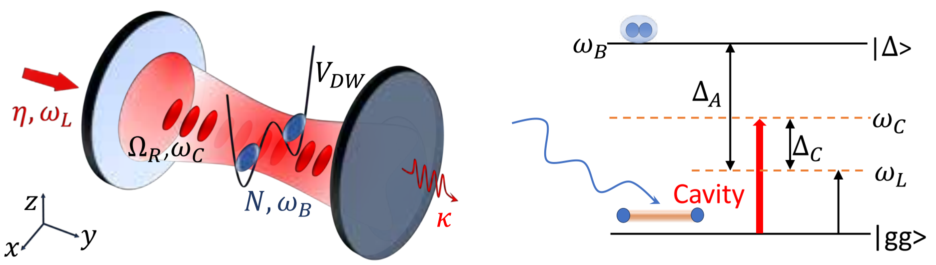


Figure 1: **Left**: The scheme of the setup. N ultracold bosonic atoms are confined in a double-well potential V_{DW} inside an optical cavity. The laser pump η with frequency ω_L enters from one of the mirrors of the cavity with photon loss rate κ. Ω_R denotes the coupling of atom pairs with photons. **Right**: The diagram of the energy levels of atomic pairs gg and the molecule Δ. Δ_A and Δ_C are detunings from the molecular state and the cavity photon, respectively.

[1] H. Konishi, K. Roux, V. Helson, and J.-P. Brantut, *Universal pair polaritons in a strongly interacting Fermi gas*, Nature **596**, 509 (2021).

[2] T. Zwettler, F. Marijanović, T. Bühler, S. Chattopadhyay, G. Del Pace, L. Skolc, V. Helson, S. Uchino, E. Demler, J.-P. Brantut, *Cavity-mediated charge and pair-density waves in a unitary Fermi gas*, arXiv:2503.05420 (2025).

[3] S. Sharma, J. Chwedeńczuk, T. Wasak, *Engineering interactions by collective coupling of atom pairs to cavity photons for entanglement generation*, Phys. Rev. Research **7**, L012038 (2025).

Is Diamagnetism Really Acausal?

N. Westerberg[1], S. M. Barnett[1]

[1]*School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, United Kingdom*

A diamagnet opposes applied magnetic fields. This is, of course, well known and has been measured and treated theoretically countless times in the past century [1]. The effect is typically weak but it is ubiquitous and present in some form or another in a wide class of materials and optical media, including single atoms [2]. Nevertheless, it is also known that there is a long-standing problem with our treatment and understanding of diamagnetism: it is in conflict with the principle of causality [3]. Nature naturally does not mind this, and experiments show diamagnetic responses from magnetic media. However, this conflict has had the effect of limiting our ability to study effects in, and around, diamagnetic media. Importantly, all diamagnetic media has had to be explicitly excluded from the theory of macroscopic quantum electrodynamics – our current best theory for explaining light-matter interactions that involve macroscopic fields and media; everything from spontaneous decay and photon production to Casimir, Casimir-Polder, and medium-assisted van der Waals forces.

To be precise, one can show that diamagnetism ought to be impossible, based on the seemingly innocuous assumptions that the diamagnet (1) obeys causality and (2) is passive (i.e., energy is lost, rather than gained inside a diamagnetic medium) [3]. These assumptions, as embodied in the Kramers-Kronig relations [4, 5], produce the inconsistency. This enigma have received intermittent attention over the last hundred years. We present a resolution to this issue [6], which also explains the absence of observed dia-electric responses in media. In the process, we expose some of the short-comings in earlier analyses that have kept the paradox alive. I will end with discussing some implications this has for spontaneous decay processes and diamagnetic metamaterials.

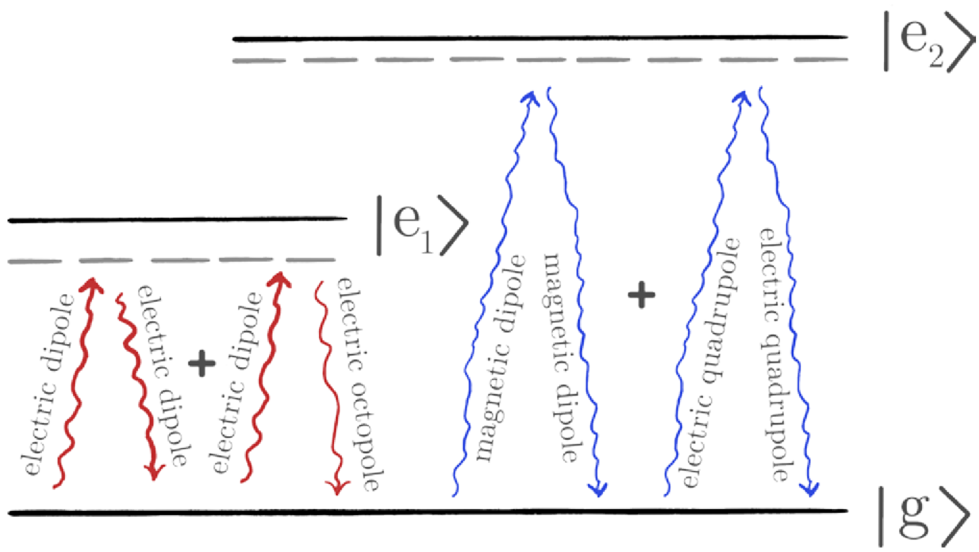


FIG. 1: Transitions involved in the resolution of the diamagnetism-causality conflict.

References

[1] J. H. van Vleck, *The theory of electric and magnetic suceptibilities* (Oxford University Press, 1932).

[2] W. Nolting and A. Ramakanth, *Quantum theory of magnetism* (Springer Verlag, Berlin, 2009).

[3] L. D. Landau and E. M. Lifshitz *Electrodynamics of continuous media* (Pergammon, Oxford, 1960).

[4] H. A. Kramers, Atti Cong. Intern. Fisica (Transactions of the Volta Centenary Congress) Commo **2**, 545 (1927).

[5] R. de L. Kronig, J. Opt. Soc. Am. **12**, 547 (1926).

[6] N. Westerberg, S. M. Barnett, arXiv:2501.13098/arXiv:2505.10612

POSTERS

Single-qubit quantum gate at an arbitrary speed

S. Ahn[1], K. Park[2], D. Cho[2], M. Lim[2], T. Choi[3], A. S. Moskalenko[1]

[1]*Department of Physics, KAIST, Daejeon 34141, Republic of Korea*
[2]*Department of Mathematical Sciences, KAIST, Daejeon 34141, Republic of Korea*
[3]*Department of Physics, Ewha Womans University, Seoul 03760, Republic of Korea*

Quantum information processing comprises physical processes, which obey the quantum speed limit (QSL): high speed requires strong driving. Single-qubit gates using Rabi oscillation, which is based on the rotating wave approximation (RWA), satisfy this bound in the form that the gate time T is inversely proportional to the Rabi frequency Ω, characterizing the driving strength. However, if the gate time is comparable or shorter than the qubit period $T_0 \equiv 2\pi/\omega_0$, the RWA actually breaks down since the Rabi frequency has to be large compared to the qubit frequency ω_0 due to the QSL, which is given as $T \gtrsim \pi/\Omega$. We show that it is possible to construct a universal set of single-qubit gates at this strong-coupling and ultrafast regime, by adjusting the central frequency ω and the Rabi frequency Ω of the driving pulse (Fig. 1). We observe a transition in the scaling behavior of the central frequency from the long-gate time regime ($T \gg T_0$) to the short-gate time ($T \ll T_0$) regime, as shown in Fig. 1(c). In the former, the central frequency is nearly resonant to the qubit, i.e., $\omega \simeq \omega_0$, whereas in the latter, the central frequency is inversely proportional to the gate time, i.e., $\omega \sim \pi/T$. We identify the transition gate time at which the scaling exponent n of the optimal central frequency $\omega \sim T^n$ changes from $n = 0$ to $n = -1$ (see the gray dotted lines in Fig. 1). In the frequency domain, we find that the Fourier component of the driving pulse at the qubit frequency is nearly constant of T and converges to the half of the gate angle in both long- and short-gate time limits.

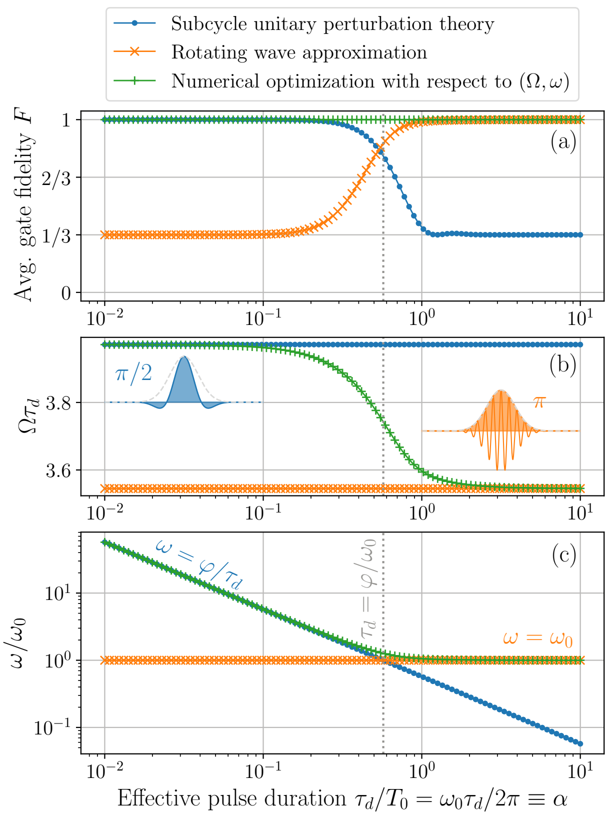


FIG. 1: Average gate fidelity with corresponding Rabi frequency Ω and central frequency ω. The pulse shape is $\Omega f(t) = \Omega f_0(t)\cos(\omega t)$ with envelope $\Omega f_0(t) = \Omega \exp[-(2t/\tau_d)^2]$. The gate time is $T = 5\tau_d$. Gray dotted vertical lines show the pulse duration at the transition from the subcycle to the multicycle regime, where the exponent of τ_d in the expression for $\omega \sim \tau_d^n \sim T^n$ changes from $n = -1$ to $n = 0$. The proportionality constant φ is determined by the subcycle unitary perturbation theory.

Optimized Error Filtration for Noise Mitigation in Quantum Systems

Aaqib Ali[1], Giovanni Scala[1], Cosmo Lupo[1]
[1]University of Bari Aldo Moro, Bari, Italy

Abstract

Error filtration is a hardware-based noise mitigation technique that leverages auxiliary qubits and entangling gates to suppress errors in quantum systems. While both the signal and ancillary qubits are susceptible to local noise, constructive interference—sometimes combined with post-selection—enables a reduction in the noise affecting the signal qubit. In this work, we identify the optimal entangling unitary gates that maximize interference effectiveness. Beginning with a universal gate set, we refine these gates through gradient descent or stochastic optimization of relevant functionals.

We further analyze the resilience of our optimized scheme under realistic conditions, considering the impact of noise in ancillary qubits and cross-talk between qubits. Despite these imperfections, our findings indicate that increasing the number of ancilla qubits enhances the protection of quantum information. To evaluate the performance of our method, we benchmark it against key metrics relevant to different quantum applications, including entanglement fidelity, quantum Fisher information (for quantum sensing), and CHSH value (for cryptographic tasks), using one, two, and three ancillary qubits. Additionally, for configurations with one and two ancillas, we derive explicit analytical expressions for the optimal unitary operations based on an ansatz approach.

Finally, we compare our approach with the recently proposed Superposed Quantum Error Mitigation (SQEM) method, which relies on superposition of causal orders. Our results show that, across a broad range of noise strengths, our error filtration technique can outperform SQEM in both effectiveness and robustness, making it a promising strategy for improving the reliability of near-term quantum devices.

PI-3

Imaginary Synthetic Magnetic Field for ultracold atoms

S. Alminas[1], D. Burba[1], T. Babelis[1,2], I. B. Spielman[3], G. Juzeliūnas[1]

[1] *Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio 3, LT-10257 Vilnius, Lithuania*
[2] *École Polytechnique, 91120 Palaiseau, France*
[3] *National Institute of Standards and Technology, Gaithersburg, MD 20899, USA*

The study of charged particles in magnetic field has been a fundamental topic in condensed matter physics, underlying important phenomena such as Landau levels and the quantum Hall effect. Over the last two decades methods have been developed to simulate the synthetic magnetic and thus the Landau problem for electrically neutral ultracold atoms by applying the light fields [**1**]. In traditional Hermitian systems, Landau levels arise from interaction of particles with a real-valued magnetic field, which induces cyclotron motion and results in equidistant, degenerate energy levels. Recent developments have extended these ideas into non-Hermitian systems, where imaginary gauge potentials give rise to new physical effects. In particular, a recent theoretical [**2**] study have revealed novel topological and dynamical properties unique to non-Hermitian lattice systems. On the other hand, an experimental study [**3**] demonstrated a possibility to generate an imaginary vector potential for ultracoms atoms. Yet such a vector potential is constant and thus does not yield a non-zero magnetic field.

Here we demonstrate how to generate for ultracoms atoms an inhomogeneous imaginary vector potential corresponding a non-zero imaginary magnetic field. Subsequently we study two-dimensional dilute Bose-Einstein condensate (BEC) of ultracold atoms, such as ^{87}Rb, subjected to such a imaginary magnetic field. We show that the ultracold atom platform enables exploration of previously inaccessible regimes of non-Hermitian quantum physics. Our analysis reveals non-trivial dynamics, including a drift induced by a spatially varying loss, which is not featured in conventional Hermitian systems. The study paves a way for further theoretical and experimental study of effects of imaginary synthetic magnetic fields on ultracold atoms.

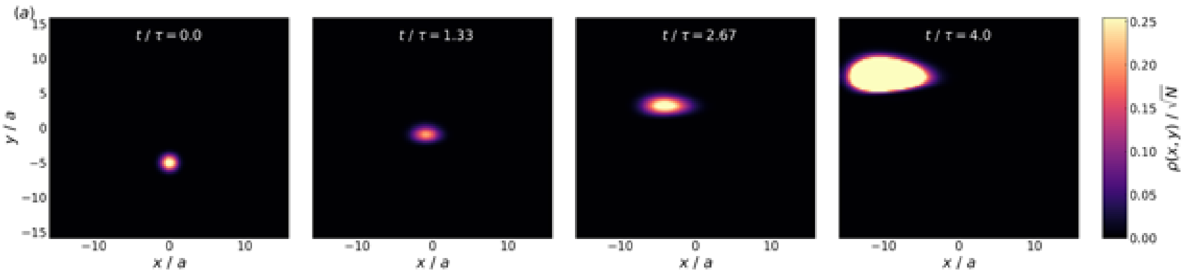


FIG. 1: Evolution of atomic density $\rho(x, y)$. Initial state is a Gaussian wavepacket with a nonzero transverse wavevector k_y. One observes expected drift due to spatially dependent non-Hermitian terms.

References

[1] N. Goldman, G. Juzeliūnas, P. Öhberg, and I. B. Spielman. Light-induced gauge fields for ultracold atoms. Rep. Prog. Phys. **77**, 126401 (2014).

[2] T. Ozawa and T. Hayata. Two-dimensional lattice with an imaginary magnetic field. Phys. Rev. B, **109**, 085113, 2024.

[3] J. Tao, E. Mercado-Gutierrez, M. Zhao, and I. Spielman. Imaginary gauge potentials in a non-hermitian spin-orbit coupled quantum gas, arXiv:2504.08614 (2025).

PI-4 Progresses toward subSQL readout and control of mechanical resonators at the mesoscale

Pierre-Edouard Jacquet[1], Michael Croquette[2], Amin Lakhal[1], Pierre-François Cohadon[1]
1. Laboratoire Kastler Brossel, 75005 Paris, France
2. Institut Néel, 38042 Grenoble, France

Interferometric measurements of mechanical displacements are nowadays limited by quantum noises in both tabletop optomechanics experiments and gravitational interferometers. These quantum noises are twofold: the Quantum Shot Noise (QSN) related to the laser's phase noise, and the Quantum Radiation Pressure Noise (QRPN) arising from the mechanical response to a fluctuating radiation pressure. Together, they enforce the so-called Standard Quantum Limit (SQL), defined as the lowest achievable noise when measuring mechanical displacements with a coherent laser field, limiting both the readout and the control of all optomechanical systems.

SubSQL displacements can, however, be observed using squeezed states of light. In the meantime, clean-room technologies have also reached a point where macroscopic mechanical resonators can be engineered to exhibit quantum behaviors under cryogenic conditions. It is therefore of interest to probe broadband subSQL mechanical spectra at low temperatures to investigate the interplay between classical and quantum physics at the mesoscopic scale [1].

Our project aims at measuring subSQL mechanical spectra of ng-scale Silicon Nitride phononic crystals (SiN PnC) by injecting squeezed light inside our fiber-based optomechanical cavity. This light source must feature a frequency-dependent squeezing angle to minimize QSN outside the resonator's bandwidth while simultaneously reducing QRPN at resonance [2].

To this end, a near-IR bowtie OPO was built at LKB and a rotation cavity was set up to induce a frequency-dependent squeezing angle by detuning it from the carrier field. This technique has also been implemented in advanced gravitational wave interferometers. A schematic diagram of the frequency-dependent squeezed light source is shown in figure 1.a. The optomechanical cavity under study is a Membrane At This Edge (MATE) system shown in figure 1.b [3]. The theoretical displacement noises obtained by injecting 6dB of squeezed light inside the cavity are plotted in 1.c. We now have a working OPO and are working towards the rotation/filter cavity optimization as well as changing the plane membrane for an ultra-high Q PnC seen in the inset of figure 1.d, while engineering the fibered micro-cavity setup [4].

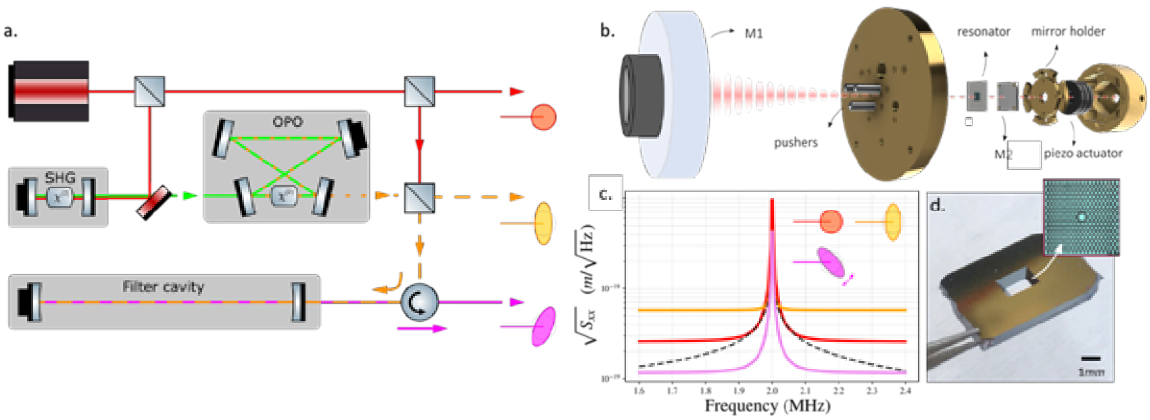


Figure 1: a) Optical setup needed to generate frequency dependent squeezing. The OPO generates squeezing with the same angle at all frequencies in the cavity bandwidth, and the filter cavity's phase response is used to induce a frequency dependent squeezing angle. b) MATE system diagram where all elements have been designed to be fixed to the cold plate of a cryostat. c) theoretical displacement noises of a 10ng PnC for sensitive experimental parameters i.e. 1mW of IR light, 6dB of squeezing, $T = 10$mK, $Q = 10^6$ and $\mathscr{F} = 20000$. d) 1mm^2 square membrane used for design validation at ambient temperature, now moving towards patterned membrane (PnC) shown in the inset.

References

[1] M. Croquette, et al," Recent advances toward mesoscopic quantum optomechanics", AVS Quantum Sci. 5 (1) 014403 (2023)
[2] H. J. Kimble, et al, "Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics". Physical Review D **65** (2), 022002 (2001)
[3] V. Dumont, et al, "Flexure-tuned membrane-at-the-edge optomechanical system," Opt. Express **27**, 25731-25748 (2019)
[4] E. Ivanov, et al, "Edge mode engineering for optimal ultracoherent silicon nitride membranes", Appl. Phys. Lett. **117**, 254102 (2020)

Gap Solitons Hosted by a Harper-Hofstadter Model with a Saturable Nonlinearity

O. Ashfield[1], **I. Carusotto**[2], **H. A. J. Middleton-Spencer**[1], and **H. M. Price**[1]
[1]*School of Physics and Astronomy, University of Birmingham*
[2]*Pitaevskii BEC Center, Università di Trento*

Nonlinearities in lattice models with non-trivial topological band structures permit soliton-like (breather) solutions that are localised in the bulk of the lattice and with energies inside of the band gap. Such solutions have been found theoretically to be "hosted" by 2D quantum Hall models [1] and, in a low power limit, behave according to the local geometry of the band structure [2]. The goal of this work is to analyse gap solitons found in a Harper-Hofstadter model with saturable nonlinearities to find a connection between the nonlinear solutions and the global properties of the topological band, specifically, the topological invariants. Current work involves studying the wavepacket dynamics of the solitons under external forces, through numerical simulations, to extract Chern numbers. This work has potential implications for both cold-atom and nonlinear photonic systems.

References

[1] Li, R. *et al.* Topological bulk solitons in a nonlinear photonic Chern insulator. *Commun. Phys.* **5**, 1–12 (2022).

[2] Marzuola, J. L., Rechtsman, M., Osting, B. & Bandres, M. Bulk soliton dynamics in bosonic topological insulators. Preprint at https://doi.org/10.48550/arXiv.1904.10312 (2019).

Optical Protocol for Generating non-Gaussian state in C-band.

Humboldt University of Berlin, Newtonstraße 15, 12489 Berlin Germany

E. Bazzazi, R. A. Kögler, L. Reichgardt, M. Schmidt, O. Benson

Humboldt University of Berlin

Non-Gaussian states play a crucial role in fault-tolerant quantum computing, where encoded information is protected from decoherence processes [1]. Certain classes of non-Gaussian states, such as coherent state superpositions known as cat states, pose challenges in generation. These are due to the complexity of breeding protocols and the limitations of their achievable output states [2,3]. Here, we explore the state engineering of squeezed coherent state superpositions (SCSS) using a catalysis protocol [4]. The output state results from a beam splitter operation applied to two input states: a vacuum squeezed state and a Fock state, followed by photon number resolved detection in one of the output arms. Our numerical simulations using the Strawberry Fields Python library [5] demonstrate the potential of this protocol to generate high-amplitude squeezed cat states with realistic quantum resources. Alongside our simulations, we propose an experimental setup for the practical realization of this protocol. We are currently developing the generation of the necessary resources, including vacuum squeezed states created by a degenerated optical parametric oscillator and heralded Fock states. Next, optical tomography of the resource states will be performed through homodyne detection. This research contributes to quantum state engineering methods, which are crucial for the generation of resource states for fault-tolerant quantum computing.

References

[1] D. S. Schlegel, A. K. Millen, J. P. Dowling, and T. B. Pittman, Phys. Rev. A **106**, 022431 (2022).

[2] K. Takase, Y. Matsuzaki, and Y. Kondo, Phys. Rev. A **103**, 013710 (2021).

[3] M. Endo, T. Mukai, K. Matsubara, and T. Tashima, Opt. Express **31**, 12865–12879 (2023).

[4] R. J. Birrittella and C. C. Leary, J. Opt. Soc. Am. B **35**, 1514–1524 (2018).

[5] N. Killoran, T. R. Bromley, J. R. Cook, D. R. Terno, and S. Lloyd, Quantum **3**, 129 (2019).

PI-7

Investigation of Silver-Aluminium Mixed Mirrors for Space Communication Applications

A. Belosludtsev[1], **I. Bitinaitis**[1], **K. Stravinskas**[1], **A. Sytchkova**[2]

[1]*Center for Physical Sciences and Technology, Savanoriu ave. 231, Vilnius 02300, Lithuania*
[2]*Optical Coatings Group, ENEA Casaccia, via Anguillarese 301, Roma 00123, Italy*

Every year it is growing the volume of information that it is necessary to transmit on Earth, in Space and in between. This is especially of high importance for space quantum communication applications. In our recent study [1], we report a systematic investigation on the Silver-Aluminium (Ag-Al) mixed mirrors. It was shown the preparation process, investigated various properties and mirrors stability to radiation. The whole mirrors structure was manufactured by magnetron sputtering technology. It was investigated mirrors with various Al concentrations. It was found that 5% of Al admixing lead to the formation smooth mirrors that might be stable during long space mission. Finally, such advanced high reflective coatings might be combined with actively cooled metallic mirror with integrated Archimedean spiral channels [2].

Acknowledgment

This project has received funding from the Research Council of Lithuania (LMTLT), agreement No [P-MIP-24-668].

References

[1] A. Belosludtsev, A. Sytchkova, I. Bitinaitis, V. Kovalevskij, Optical Materials (2025) submitted.

[2] I. Bitinaitis, K. Stravinskas, S. Borodinas, G. Mordas, A. Belosludtsev Optics and Lasers in Engineering (2025) submitted.

Topological Quasiparticles in Nonhomogeneously Polarized Airy Beams

J. Berškys[1], **S. Orlov**[1]

[1] *State research institute Center for Physical Sciences and Technology, Vilnius, Lithuania*

Electromagnetic waves are characterized by four main parameters: wavelength, phase, polarization, and amplitude. Advances in lasers, optical components, and meta-elements have driven progress in metrology, manufacturing, and quantum technologies. Manipulating these parameters enables the creation of diverse optical fields, ranging from optical tweezers and Möbius strips to non-diffracting beams and topological particles of light [**1**].

Non-diffracting beams, such as Bessel and Airy beams, exhibit unique properties like self-healing and the ability to transfer angular momentum to nanoparticles. The manipulation of polarization significantly influences the propagation dynamics of optical fields, giving rise to phenomena such as singular polarization beams and spin-orbit interactions.

Topological quasiparticles, or skyrmions—first proposed by Tony Skyrme [**2**]—have attracted considerable interest in various fields, including optics. These entities can be observed in the Stokes field domain, the electric field, and the spin of light. Optical quasiparticles have been studied in contexts such as optical lattices, light pulses, and photonic hopfions.

In this research, we investigate the topological structure of radially and azimuthally polarized Airy-like beams.

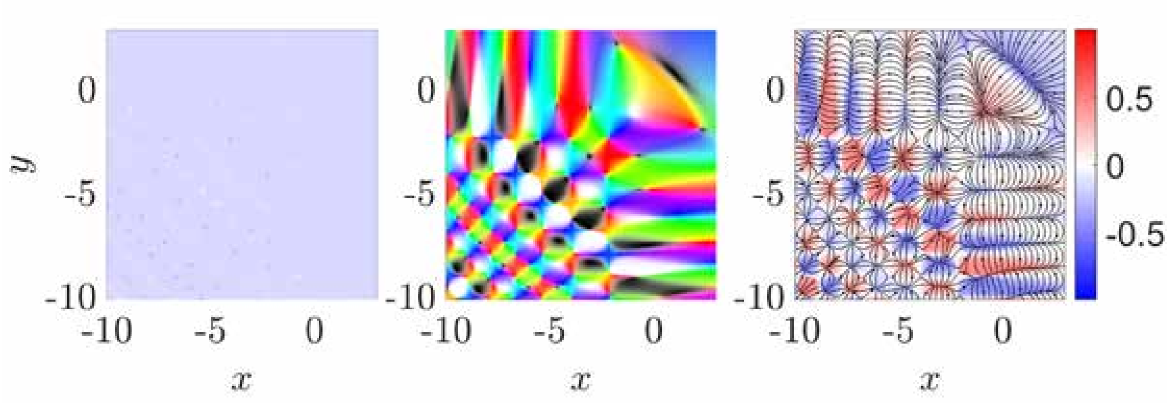


Figure 1: Topological structure distribution of the real part of the vector field $\mathbf{N}$, when $n_x = \mathrm{Re}\{N_x\}/|\mathbf{N}|$, $n_y = \mathrm{Re}\{N_y\}/|\mathbf{N}|$ and $n_z = \mathrm{Re}\{N_z\}/|\mathbf{N}|$. The skyrmionic density (a), the distribution of the transverse components' angle (hue color scheme) and magnitude of the longitudinal component (black and white color scheme) (b), and the magnitude of the longitudinal component, where the black streamlines with arrows, shows the orientation of the transverse field (c). The parameters of the simulation are: the decay factor $a_x = a_y = 0.2$, the normalization distances $x_0 = y_0 = 1$, the distance from the focus $z = 4$, and the wavenumber $k = 2\pi$.

References

[1] Y. Shen, H. Wang, and S. Fan, "Free-space topological optical textures: tutorial," *Adv. Opt. Photon.*, vol. 17, pp. 295–374, 2025.

[2] T. H. R. Skyrme, "A non-linear field theory," *Proc. R. Soc. Lond. A Math. Phys. Sci.*, vol. 260, no. 1300, pp. 127–138, 1961.

Catability as a direct metric for evaluating superposed coherent states

Š. Bräuer, J.Provazník, V. Kala, P. Marek

Department of Optics, Faculty of Science, Palacký University, 17. Listopadu 12, 77146 Olomouc, Czech Republic

Cat states, also known as superposed coherent states, represent a quantum superposition of two classical states, making them valuable for discussions about the foundations of quantum mechanics, but they also have a place in practical applications. Applications range from the use of cat states directly in specific protocols [1, 2, 3] to their role in generating more complex quantum states through breeding techniques [4, 5, 6]. Their versatility arises from their inherently quantum, non-Gaussian nature. However, experimental preparation of superposed coherent states remains a challenge, as their non-Gaussian properties are highly susceptible to noise and loss [7, 8, 9].

The quality of experimentally prepared states is typically evaluated by using fidelity, which measures the geometric overlap between two quantum states. However, fidelity is often challenging to interpret and requires full-state tomography for an accurate assessment of the experimental data. Moreover, it does not account for specific characteristics of cat states, such as their non-Gaussian nature.

We propose a novel approach to evaluate and identify cat states based on a directly observable operator. The eigenstates of this operator correspond to both even and odd cat states. Utilizing this operator, we introduce a measure — referred to as CATABILITY — that quantifies the cat-like nature of quantum states. This method is grounded in the general concept of nonlinear squeezing [10], enabling the assessment of quantum states and the identification of their properties depending on the variance in the chosen operator. In our case, we apply nonlinear squeezing specifically to cat states.

The key advantage of our approach lies in its direct measurability, which eliminates the need for full-state tomography. This means that the number of measurements can be rapidly reduced, and only the power of the mean values of the photon number operator needs to be measured.

[1] T. C. Ralph et al.: Phys. Rev. A **68**, 042319 (2003)

[2] A. P. Lund et al.: Phys. Rev. Lett. **100**, 030503 (2008)

[3] J. Hastrup et al.: Phys. Rev. Res. **4**, 043065 (2022)

[4] A. P. Lund et al.: Phys. Rev. A **70**, 020101 (2004)

[5] D. V. Sychev et al.: Nat. Photonics **11**, 379 (2017)

[6] J. Hastrup et al.: Phys. Rev. Lett. **128**, 170503 (2022)

[7] M. Yukawa et al.: Opt. Express **21**, 5529 (2013)

[8] M. Eaton et al.: Quantum **6**, 769 (2022)

[9] J. Provazník et al.: arXiv:2406.01081 (2024)

[10] Š. Bräuer et al.: arXiv:2503.09210 (2025)

Stationary Vortex States in Two-Component Bose–Einstein Condensates

Y. Braver,[1] D. Burba,[1] G. Žlabys,[2] E. Anisimovas,[1] Th. Busch,[2] and G. Juzeliūnas[1]

[1] *Institute of Theoretical Physics and Astronomy, Faculty of Physics, Vilnius University, Vilnius, Lithuania*

[2] *Quantum Systems Unit, Okinawa Institute of Science and Technology Graduate University, Onna, Okinawa, Japan*

Bose–Einstein condensates (BECs) provide a unique platform for studying quantum fluid dynamics, where macroscopic quantum phenomena such as superfluidity and quantised vortices emerge. Vortices in BECs are characterised by phase singularities in the condensate wave function, and they reveal insights into angular momentum quantisation and topological defects in quantum systems [1]. The study of vortices in degenerate bosonic and fermionic gases has broad implications, ranging from quantum turbulence [2] to connections with superconductivity [3] and the structure of neutron stars [4].

A key challenge in the study of BEC vortices is their controlled creation and manipulation. Typically, the vortices are produced using optical means: through phase imprinting [5], stirring with a laser beam [6], or using beams carrying orbital angular momentum, such as Laguerre–Gaussian (LG) beams [7]. Relatedly, an interesting playground for optical experiments is provided by the so-called Λ-type coupling configuration and the presence of a dark state. This optical coupling scheme has been used to, among others, realise atom control at subwavelength resolution [8], make narrow structures in the BEC [9], and to create vortices in BEC using Raman-type schemes [10].

In this work [11], we study the vortex states that emerge as a result of continuous interaction of a trapped two-component BEC mixture with the light fields in a Λ-type configuration. Specifically, we consider the case where one of the two beams is an LG beam, and investigate the resulting stationary states. The angular momentum of $\ell\hbar$ per photon carried by the LG beam leads to either one or both components being in a vortex state, with their vorticities differing by ℓ units. Depending on the ratio of magnitudes of the two beams, the ground state may have an unconventional structure, whereby the component having a vortex is surrounded by the second one which is vortex-free. The density profile of the vortex demonstrates a strong degree of localisation — away from the vortex core, the density falls off as $[1 + (\rho/a)^2]^{-1/2}$, where ρ is the distance from the core and a is a controllable parameter. Such a vortex can be moved around the trap by moving the laser beams. Provided the movement speed is less than approximately half the speed of sound in the condensate, the shape of the vortex retains its structure during the movement, and the density of the second component does not get distorted as well.

We support our findings with analytical arguments based on the approximate one-dimensional Gross–Pitaevskii equation (GPE) for the dark state, which features a geometric vector potential term. Additionally, we present numerical solutions of the full GPE system describing the Λ-coupled three-level system.

[1] A. L. Fetter and A. A. Svidzinsky, Vortices in a trapped dilute Bose-Einstein condensate, J. Phys.: Condens. Matter **13**, R135 (2001), arXiv:cond-mat/0102003.

[2] M. Tsubota, M. Kobayashi, and H. Takeuchi, Quantum hydrodynamics, Phys. Rep. **522**, 191 (2013), arXiv:1208.0422.

[3] K. Harada, T. Matsuda, J. Bonevich, M. Igarashi, S. Kondo, G. Pozzi, U. Kawabe, and A. Tonomura, Real-time observation of vortex lattices in a superconductor by electron microscopy, Nature **360**, 51 (1992).

[4] P. Magierski, A. Barresi, A. Makowski, D. Pęcak, and G. Wlazłowski, Quantum vortices in fermionic superfluids: From ultracold atoms to neutron stars., Eur. Phys. J. A **60**, 186 (2024), arXiv:2406.14158.

[5] Ł. Dobrek, M. Gajda, M. Lewenstein, K. Sengstock, G. Birkl, and W. Ertmer, Optical generation of vortices in trapped Bose-Einstein condensates, Phys. Rev. A **60**, R3381 (1999), arXiv:cond-mat/9907452.

[6] K. W. Madison, F. Chevy, W. Wohlleben, and J. Dalibard, Vortex formation in a stirred Bose-Einstein condensate, Phys. Rev. Lett. **84**, 806 (2000), arXiv:cond-mat/9912015.

[7] K.-P. Marzlin, W. Zhang, and E. M. Wright, Vortex coupler for atomic Bose-Einstein condensates, Phys. Rev. Lett. **79**, 4728 (1997), arXiv:cond-mat/9708198.

[8] A. V. Gorshkov, L. Jiang, M. Greiner, P. Zoller, and M. D. Lukin, Coherent quantum optical control with subwavelength resolution, Phys. Rev. Lett. **100**, 093005 (2008), arXiv:0706.3879.

[9] H. R. Hamedi, G. Žlabys, V. Ahufinger, T. Halfmann, J. Mompart, and G. Juzeliūnas, Spatially strongly confined atomic excitation via a two dimensional stimulated Raman adiabatic passage, Opt. Express **30**, 13915 (2022), arXiv:2111.03750.

[10] G. Nandi, R. Walser, and W. P. Schleich, Vortex creation in a trapped Bose-Einstein condensate by stimulated Raman adiabatic passage, Phys. Rev. A **69**, 063606 (2004).

[11] Y. Braver, D. Burba, S. S. Nair, G. Žlabys, E. Anisimovas, T. Busch, and G. Juzeliūnas, Light-induced localized vortices in multicomponent Bose-Einstein condensates (2025), arXiv:2506.08683.

PI-11

Two-Point Resolution in Defocused Coherent Imaging: Theoretical Framework and Implications for High-Speed 3D Reconstruction

A. Brunetti[1], G. Massaro[1,2], S. de Gioia[1,2], Francesco V. Pepe[1,2] and M. D'Angelo[1,2]

[1]*Dipartimento di Fisica, Universita degli Studi di Bari, 70125 Bari, Italy*
[2]*Istituto Nazionale di Fisica Nucleare, Sezione di Bari, 70125 Bari, Italy*

Quantum imaging has emerged as a powerful tool for high-resolution imaging by exploiting quantum entanglement and classical correlations [1]. Techniques such as sub-shot-noise imaging [2], quantum lithography [3], and quantum-enhanced resolution leverage nonclassical photon statistics to surpass classical limits. Among these, ghost imaging [4] stands out for its ability to reconstruct images using single-pixel detectors and correlations, demonstrating robustness against noise and scattering [5]. A significant advancement in this field is correlation plenoptic imaging (CPI) [6], which combines light intensity and photon correlations to achieve high-resolution 3D imaging, even in defocused conditions. Unlike conventional incoherent systems, CPI provides resolution independent of the numerical aperture (NA), overcoming the depth-of-field limitations imposed by geometric blurring [7].

Recent studies have shown that, for purely absorbative samples, similar performance can be achieved by using spatially coherent illumination [8], simplifying optical designs and improving signal-to-noise ratios. These developments challenge traditional imaging paradigms, where incoherent systems excel in simplicity but struggle with thick or defocused samples due to NA-dependent blurring. Coherent illumination offers a solution to the resolution-depth-of-field trade-off, enabling high-resolution imaging even in defocused conditions.In this work, we present a modified two-point resolution criterion [9] for defocused coherent imaging systems, demonstrating that resolution degradation follows a square-root dependence on defocusing distance—independent of numerical aperture (NA)—in stark contrast to the NA-dependent linear deterioration of incoherent systems (Figure 1). This behavior, rooted in diffraction rather than geometric blurring, challenges conventional imaging paradigms established since Abbe's formulation of the diffraction limit. Our contrast-based analysis reveals that image degradation in coherent systems arises from two equally weighted factors: diffraction-induced broadening and interference-mediated contrast reduction, as quantified through fidelity metrics (colored regions in Figure 1). Spatial coherence thus enables computationally efficient light-field imaging, where lateral resolution is invariant under defocusing conditions and axial resolution is defind by the dominant NA of the optical system. We also show that the incorporation of annular illumination strategies significantly enhances imaging speed by optimizing dataset acquisition and reducing redundant information within the standard 4D dataset used in light-field reconstructions. Our results thus establish that the resolution-preserving characteristics of coherent imaging can be harnessed for high-speed volumetric imaging, with applications in biomedical imaging, optical metrology, and microscopy.

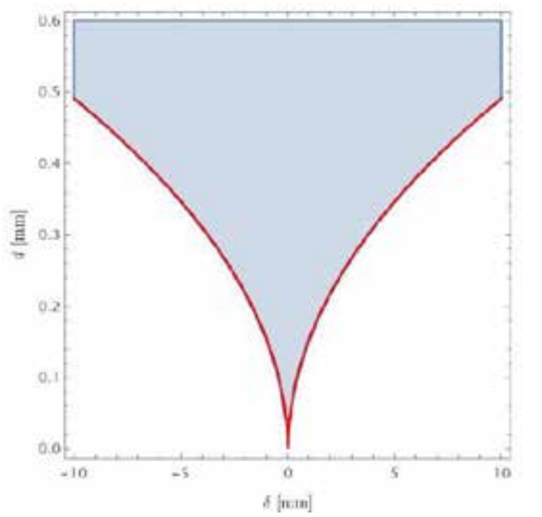


Figura 1The light blue area represents the region where the coherent images of the two Gaussian slits are resolvable in the sense of the contrast criterion for an arbitrarily chosen contrast threshold of 20. The red curve represents the approximated resolution limit curve derived under the assumption of an infinite NA

Acknowledgments
This work received funding from the European Defence Fund (EDF) under grant agreement 101103417 – project ADEQUADE. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the granting authority can be held responsible for them.

References

[1] J. Garrison, R. Chiao, Quantum Optics (2008).
[2] N. Samantaray et al., Light Sci. Appl. **6**, e17005 (2017).
[3] M. D'Angelo et al., Phys. Rev. Lett. **87**, 013602 (2001).
[4] T.B. Pittman et al., Phys. Rev. A **52**, R3429 (1995).
[5] X. Chen et al., Opt. Express **18**, 10579 (2010).
[6] M. D'Angelo et al., Phys. Rev. Lett. **116**, 223602 (2016).
[7] G. Massaro et al., Sci. Rep. **12**, 16823 (2022).
[8] G. Massaro et al., Laser Photonics Rev. **18**, 2301155 (2024).
[9] G. Massaro et al., Photonics **11**, 1203 (2024).

Towards a Quantum Interface Between Trapped Ions and Telecom Photons

V. Cambier[1], L. Gros Desormeaux[1], I. Pio di Siomeone[1], JP. Likforman[1], L. Guidoni[1], S. Ducci[1]

Université Paris Cité, CNRS UMR 7162, Laboratoire Matériaux et Phénomènes Quantiques, 75013, Paris, France

Recent advances in quantum physics have led to the emergence of new disciplines such as quantum computing, quantum simulation, and quantum communication, which are at the heart of the ongoing deployment of quantum technologies. Our team has developed two experimental components using complementary quantum platforms: laser-cooled trapped ions and semiconductor sources of correlated photons. In order to bridge these two components, we started developing a hybrid quantum interface. The deployment of this interface seeks to address one of the underlying challenges of quantum communication networks: the connection between static qubits (in this case, trapped ions) and flying qubits (single photons).

Quantum networks have begun to be set up, paving the way for long-distance entanglement tests and encrypted key distributions for network security. However, interfacing them with static qubits (in this case, trapped ions) remains a major challenge. Trapped ions are a first-rate choice for the realization of quantum bits, due to their long coherence time and the record fidelity obtained for logic gates.

In this work, we present our approach to develop this quantum interface. We worked on a new experimental setup to collect spontaneous photons entangled with the internal states of the ions. We trap strontium ions and chose a specific wavelength (1092 nm) for the photons spontaneously emitted by the trapped ions. After a first step dedicated to prove the « single-photon » behavior of the emitted photons, we plan to develop an original entanglement swapping protocol. This protocol would be based on a non-degenerate spontaneous parametric down-conversion (SPDC) source in order to enable long-distance quantum communication. This source would generate photon pairs at 1092 nm—matching the strontium ion's transition wavelength—and 1550 nm, which is optimal for fiber transmission.

Can Quantum Jumps Improve Quantum-Battery Charging?

G. Chimczak, E. Lange, A. Kowalewska-Kudłaszyk

[1] *Faculty of Physics and Astronomy, Adam Mickiewicz University, Poznań, Poland*

Quantum jumps play a negative role during the charging of the quantum battery, for two reasons. Firstly, quantum jumps occur from higher energy levels to lower energy levels, while the main goal of charging is to populate higher energy levels. Secondly, intrinsic randomness of quantum jumps introduces decoherence, while the charging speedup observed in quantum batteries is a result of interference. Therefore, it is commonly believed that quantum jumps cannot be useful in the task of charging a quantum battery.

Usually quantum batteries are modeled by a collection of N two-level systems. This simple model has an important drawback - if the high-energy level is metastable then it is very hard to couple the atomic transition to the optical cavity mode, because the transition is electric-dipole-forbidden. The interaction of atoms with the cavity mode is crucial to observe interference accelerating the charging process. On the other hand, if the high-energy level is not metastable then the energy cannot be stored for long time in such system.

Here, we consider a quantum battery consisting of N three-level Λ-type atoms. Initially, the quantum battery is discharged, i.e., all atoms are prepared in the ground state. The aim of the charging process is to transfer the population from the ground state to the metastable state via an excited state. We show that if quantum jumps are directional, i.e., an atom from the excited state can jump only to the metastable state, then quantum jumps play a positive role: they decrease the charging time and increase the maximal energy stored in the battery [1]. Moreover, we show that it should be possible to implement this idea using ^{87}Rb atoms.

References

[1] E. Lange, G. Chimczak and A. Kowalewska-Kudłaszyk, in preparation.

How Likely Are You to Observe Non-locality with Imperfect Detection Efficiency and Random Measurement Settings?

Paweł Cieśliński,[1] Mateusz Kowalczyk,[1] Wiesław Laskowski,[1] and Tamás Vértesi[2]

[1] *Institute of Theoretical Physics and Astrophysics, University of Gdańsk, 80-308 Gdańsk, Poland*
[2] *HUN-REN Institute for Nuclear Research, P.O. Box 51, H-4001 Debrecen, Hungary*

One of the main problems in taking full advantage of Bell non-locality is the imperfect detection efficiency, which becomes especially daunting in the case of long-distance Bell experiments. On the other hand, a large separation between distinct parties complicates calibration and establishing a common reference frame for the measurement settings. Randomised measurements have proven themselves useful in many areas of quantum information [1, 2], including the possibility of certifying non-locality without the need for a shared reference frame. Thus, incorporating detection efficiency into the random measurements Bell test can address both of the mentioned problems.

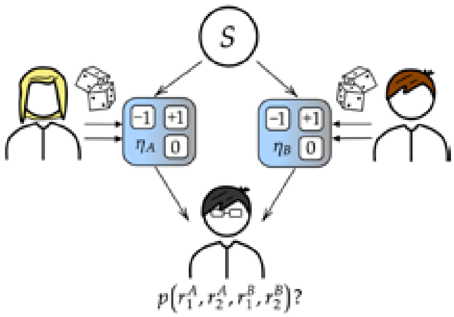


FIG. 1. A quantum state is distributed between Alice and Bob. Using their imperfect apparatus with detection efficiencies η_A and η_B respectively they perform two randomly chosen measurements each. Once they gather the statistics they send it to an external referee and ask if there exists a local realistic explanation for the experimental data. The probability of Bell inequality violation encompasses the average number of negative answers to this question.

Imagine a two-party scenario where Alice and Bob perform two Haar randomly chosen measurements (i.e. measurement directions chosen uniformly and randomly from a Bloch sphere) on a shared state with imperfect detectors, see Fig. 1. They gather their statistics and send it to an external referee who checks whether there exists a local realistic model compatible with the obtained information. How often will he be unable to do so? Formally the probability of Bell inequality violation is defined as $\mathcal{P}_V = \int d\Omega f(\Omega)$ [3], where the integral goes over all the parameters within a Bell scenario and f is a function that outputs 1 whenever these parameters lead to a violation some Bell inequality and 0 otherwise. Here, we derive an analytical detection efficiency dependent lower bound on the probability of Bell inequality violation for a two-qubit maximally entangled state which is exact for correlation inequalities and perfect efficiencies. We further explore this numerically, in the three-outcome and binning models for imperfect detection efficiency, for more parties and settings using an original method based on linear programming [4]. We determined the symmetric critical efficiencies η_{crit} for the three-qubit GHZ and W state. For two parties, we recover the previously established results, while for three parties, we derive $\eta_{crit} = 2/3$ within the binning model. For the GHZ state, extra no-detection outcome and two settings per party, we present an inequality with $\eta_{crit} \approx 0.7208$, which is notably less than 0.75 for. Additionally, one conclusion made in [4, 5] was that with a growing number of particles or measurement settings violation of local realism is almost certain - the so-called typicality of Bell violation. Our findings extend this result to the case of imperfect detectors and furthermore show that any drop in efficiency above the critical one can be compensated with additional settings. This shows that the misalignment of the measurement directions and a drop in detection efficiency can be overcome with a higher number of measurements.

[1] P. Cieśliński, S. Imai, J. Dziewior, O. Gühne, L. Knips, W. Laskowski, J. Meinecke, T. Paterek, and T. Vértesi, Analysing quantum systems with randomised measurements, Physics Reports **1095**, 1–48 (2024).
[2] A. Elben, S. T. Flammia, H.-Y. Huang, R. Kueng, J. Preskill, B. Vermersch, and P. Zoller, The randomized measurement toolbox, Nature Reviews Physics **5**, 9–24 (2022).
[3] A. Barasiński, A. Černoch, K. Lemr, and J. Soubusta, Genuine tripartite nonlocality for random measurements in Greenberger-Horne-Zeilinger-class states and its experimental test, Phys. Rev. A **101**, 052109 (2020).
[4] A. de Rosier, J. Gruca, F. Parisio, T. Vértesi, and W. Laskowski, Multipartite nonlocality and random measurements, Phys. Rev. A **96**, 012101 (2017).
[5] V. Lipinska, F. J. Curchod, A. Máttar, and A. Acín, Towards an equivalence between maximal entanglement and maximal quantum nonlocality, New Journal of Physics **20**, 063043 (2018).

Leveraging the Encirclement of the Exceptional Points in the Cycle of Quantum Heat Engine Described by Thermal States

Ivan Davydenko, Grzegorz Chimczak

Faculty of Physics and Astronomy, Adam Mickiewicz University, Poznań, 61-614, Poland

Quantum heat engines (QHE), meant to be counterparts to classical thermal machines, operate on quantum objects or systems that demonstrate quantum effects. Over the last decade, they have drawn significant attention due to their application in miniature and low-power systems, testing quantum thermodynamical limits and their role in biomolecular processes[**1-2**]. QHEs have been implemented in the form of microscopic electro-mechanical systems[**3**] along with extremal forms such as single ions[**4**], quantum dots[**1**], or ultracold bosonic atoms[**5**].

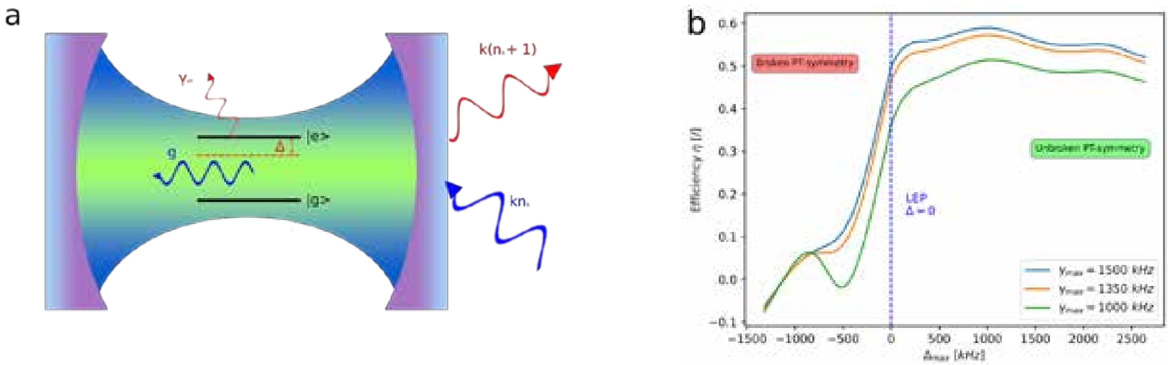


FIG. 1: (a) The model of thermal quantum heat engine. Two-level atom in an optical cavity. The cavity is in thermal contact with the photon reservoir. g – coupling strength between the atom and the cavity, κ – leakage rate of the cavity, γ_{eff} – effective dumping rate of the atom, Δ – detuning from the resonance between the frequency of the atom and the frequency of the cavity, n_s – the average number of photons in the cavity. (b) The efficiency of the QHE as a function of the Δ_{max} for different γ_{max}. The blue vertical line depicts the LEP ($\Delta = 0$).

The effect of the Liouvillian Exceptional Points (LEP) on QHE performance has been studied over the past few years. It has been demonstrated that by encircling the LEP it is possible to enhance the performance of QHE realized with $^{40}Ca^{+}$ ion[**4**]. However, such QHE is pumped by a laser field described by the coherent state. Therefore, it shouldn't be considered the quantum analog of a classical thermal machine, which uses a chaotic heat bath as an energy source. In our presentation, we demonstrate the implementation of QHE described by the thermal states. Our model is shown in panel (a) of Fig. 1 and consists of a 2-level atom coupled with an optical cavity by the coupling strength g; cavity losses are described by κ. Thermal photons are pumped from a photon reservoir. We implement the quantum Otto cycle by varying detuning from the resonance Δ and effective dumping rate γ_{eff} in time. As demonstrated in panel (b) of Fig. 1, a significant boost in the efficiency of a QHE is observed when the cycle encircles the LEP. Moreover, performance is enhanced by encircling more LEPs, which was realized by performing cycles for various γ_{max}. In conclusion, we show the possibility of exploiting the effects in the vicinity of EPs to improve the performance of QHE described by thermal states.

References

[1] Josefsson, M., Svilans, A., Burke, A.M. et al. Nature Nanotech 13, 920–924 (2018).

[2] Keye Zhang, Francesco Bariani, and Pierre Meystre, Phys. Rev. Lett. 112, 150602 (2014).

[3] Steeneken, P., Le Phan, K., Goossens, M. et al. Nature Phys 7, 354–359 (2011).

[4] J.-T. Bu, J.-Q. Zhang, G.-Y. Ding, J.-C. Li, J.-W. Zhang, B. Wang, W.-Q. Ding, W.-F. Yuan, L. Chen et al. Phys. Rev. Lett. 130, 110402 (2023).

[5] O. Fialko and D. W. Hallwood, Phys. Rev. Lett. 108, 085303 (2012).

Cross-talk in continuous-variable quantum passive optical networks

Ivan Derkach, Olena Kovalenko, Akash nag Oruganti, Vladyslav C. Usenko

Department of Optics, Faculty of Science, Palacky University, Olomouc, Czech Republic

Multiplexing broadcasting protocols [**1**] is crucial for network expansion, however in a practical setting multiplexed signal modes will be (to some extent) mutually coupled, and any resulting cross-talk will be detrimental for the performance. We investigate Continuous-Variable Quantum Key Distribution broadcasting protocols, and model the cross-talk by a linear coupling of two broadcasted signal modes. We evaluate the secret key rate between Alice$_j$ and Bob$_{j,1}$ with cross-talk parametrized by linear coupling strength t_A and normalize it with the secret key rate K (SKR) in absence of cross-talk $K(t_A = 1)$, with results shown in Fig. 1 (a). This highlights the relative key loss due to cross-talk and that already weak signal coupling will have destructive influence on the overall network performance, even when channel noise $\epsilon_j = 0$ (in broadcasted mode j) is negligible. An advanced data analysis and post-processing is required to decouple the modes and at least partially restore the performance [**4**].

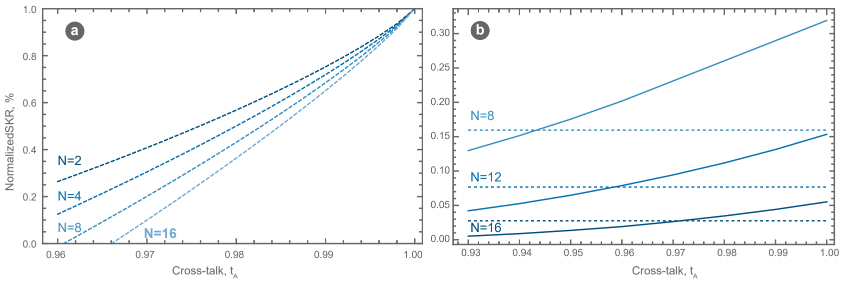


Figure 1: **(a)** Normalized key rate $K(t_A)/K(t_A = 1)$ of untrusted broadcasting protocol for single Bob dependency on the cross-talk t_A between multiplexed networks. Parameters: $\beta = 95\%$, $V_j = 3.5$ SNU (close to optimal), detector efficiency $\tau_j = 86\%$, channels loss $\eta_j = 2dB$, channel noise is absent $\varepsilon_j = 0$, and electronic noise $\nu_j = 5\%$ SNU. (**c**) The total secure key rate comparison, as in (b), for different network sizes $N = 8, 12, 16$ but with realistic parameters: $\beta = 95\%$, $V_j = 4$ SNU, detector efficiency $\tau_j = 86\%$, channels loss $\eta_j = 2dB$, excess noise $\varepsilon_j = 5 \cdot 10^{-3}$ SNU, and electronic noise $\nu_j = 1\%$ SNU.

Verifying signal reception by trusted users allows to reduce the effect of cross-talk in the broadcasted network. We investigate at which point does the total key in two networks falls below the key generated within single network without any cross-talk $K_{j=1}(t_A) + K_{j=2}(t_A) < K_{j=1}(t_A = 1)$ (indicated by dashed lines on Fig.1**c**). Even under realistic conditions (with non-negligible excess noise $\varepsilon > 0$, imperfect detectors $\tau \neq 1$ and limited reconciliation efficiency $\beta < 1$) user trust leads to a positive key rate performance at larger cross-talk values. Secret key rate in two networks falls under the total key of a single network without cross-talk at relatively higher values of t_A. With 16 simultaneous users in one network at cross-talk $t_A < 0.97$ two networks can still yield large key rate output.

We evaluated broadcasting CV-QKD protocols using coherent and squeezed states under various trust scenarios, determining the maximum users supported in practical settings and showing that even minor crosstalk significantly affects key rates, with end-user trust enhancing performance and feasibility for real-world applications.

References

[1] Hajomer, Adnan AE and Derkach, Ivan and Filip, Radim and Andersen, Ulrik L and C. Usenko, Vladyslav and Gehring, Tobias, Light: Science & Applications **13**-1, 291 (2024).

[2] Kovalenko, Olena and Usenko, Vladyslav C and Filip, Radim, Optics Express **29**-15, 24083–24101 (2021).

[3] Kovalenko, Olena and Ra, Young-Sik and Cai, Yin and Usenko, Vladyslav C and Fabre, Claude and Treps, Nicolas and Filip, Radim, Photonics Research **9**-12, 2351–2359 (2021).

High-dimensional photonic circuits using liquid-crystal metasurfaces

S. Dey[1], **P. Cameron**[1,2], **F. Di Colandrea**[1], **L. Marrucci**[1], **F. Cardano**[1†]

[1] Physics Department, University of Naples, Federico II, Napoli (Italy)
[2]Scuola Superiore Meridionale, Napoli (Italy)
[†]Corresponding author: filippo.cardano2@unina.it

An essential component of quantum information processing is the ability to encode information in on quantum states and perform unitary transformations. Photonic states are a promising candidate for this and, in particular, states encoded in high-dimensional degrees of freedom of photons have received attention in recent years due to their potential for higher information capacity and resistance to noise and decoherence. One promising technique for performing unitaries on photonic states is Multi-Plane Light Conversion (MPLC), which acts on spatial modes of light through alternating free-space propagation and phase modulations. MPLC offers a powerful approach for achieving arbitrary unitary operations in high-dimensional spatial mode bases. Traditionally, MPLC systems rely on spatial light modulators (SLMs) or refractive optics (*1*, *2*), but these approaches face scalability challenges e.g. due to losses and inherent reflective geometries.

In this work, we explore an alternative implementation using liquid crystal metasurfaces (LCMSs) and structured light modes, specifically the transverse spatial modes i.e. position and momentum. Essentially, LCMSs are a thin layer of liquid crystals whose optic axis can be arbitrarily patterned in the transverse plan allowing for complex phase and polarisation control (*3*). They enable transmissive operation, reduce optical losses, and enhance stability, making them ideal for scalable quantum photonic circuits. We fabricate these devices and investigate the MPLC technique in transmission, aiming to develop quantum circuits capable of performing unitary transformations in greater than 25 spatial modes, surpassing the current state-of-the-art (*4*). As a proof of concept, we will demonstrate the implementation of a high-dimensional Hadamard transformation - an essential operation for many techniques in quantum computing, quantum key distribution (QKD), and state tomography - with a limited set of transverse spatial modes (d=4). To do this, we have developed an optimization approach based on the typically-used wavefront matching algorithm to generate the required phase modulations of our plates. Using this numerical optimization, we found the ideal experimental parameters, allowing us to move towards a practical demonstration of our novel liquid-crystal-based MPLC. Following this, we plan to scale our approach to a higher number of spatial modes and to incorporate polarization, which will double the size of the Hilbert to which we have access. Such advancements pave the way for a wide range of quantum information applications, such as QKD, photonic quantum computing, quantum state measurement, and more.

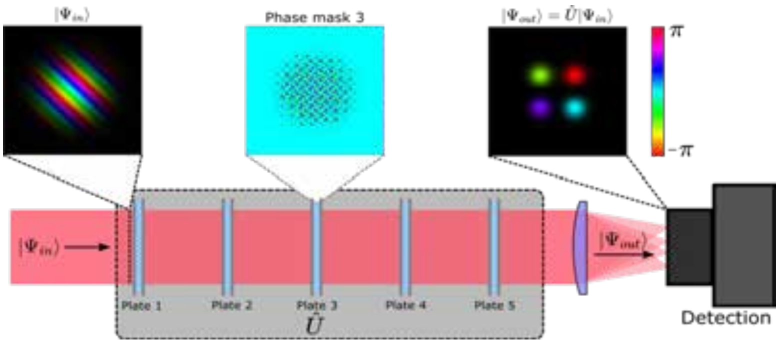


FIG. 1: Sketch of an MPLC in transmissive configuration performing the Hadamard transformation

References

[1] N. K. Fontaine et al., Nat. Commun. 10, 1865 (2019).
[2] F. Brandt, M. Hiekkamäki, F. Bouchard, M. Huber, R. Fickler, Optica. 7, 98–107 (2020).
[3] A. Rubano, F. Cardano, B. Piccirillo, L. Marrucci, JOSA B. 36, D70–D87 (2019).
[4] O. Lib, Y. Bromberg, Nat. Photonics. 18, 1218–1224 (2024) B. B. Mandelbrot, Multifractals and 1/f Noise (Springer, New York, 1999).

Optimal and effective signal-processing tools for atomic magnetometers

K. Dilcher[1], P. Bania[2], D. Mendez Avalos[3], A. Sierant[3], M. Mitchell[3,4], J. Kołodyński[1,5]

[1] *Centre of New Technologies, University of Warsaw, Banacha 2c, 02-097 Warsaw, Poland*
[2] *AGH University of Krakow, Faculty of Electrical Engineering, Automation, Computer Science and Biomedical Engineering, Department of Automation and Robotics, al. A. Mickiewicza 30, 30-059 Krakow, Poland*
[3] *ICFO - Institut de Ciències Fotòniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain*
[4] *ICREA - Institució Catalana de Recerca i Estudis Avançats, 08010 Barcelona, Spain*
[5] *Institute of Physics, Polish Academy of Sciences, Aleja Lotników 32/46, 02-668 Warsaw, Poland*

We simulate the operation of an atomic magnetometer developed by Jiménez-Martínez et. all [**1**], being pumped by circularly polarised light and then evolving freely under the influence of a strong magnetic field. We derive and compute the (Bayesian) Cramér-Rao bound (CRB) dictating the ultimate precision in estimating the resulting Larmor frequency. We show that it can always be achieved by the prediction error method (PEM), as long as there are no restrictions on the time to process the measurement data. However, for the sampling rate employed in the experiment, whose limits we also explore, we demonstrate that the Extended Kalman Filter (EKF) and Cubatore Kalman Filter (CKF) can perform nearly as well while being importantly computationally efficient [**2**]. Last but not least, we show that both the PEM and the EKF methods can be used to accurately track time-varying signals, thus making the latter compatible with more demanding "real-time" sensing protocols.

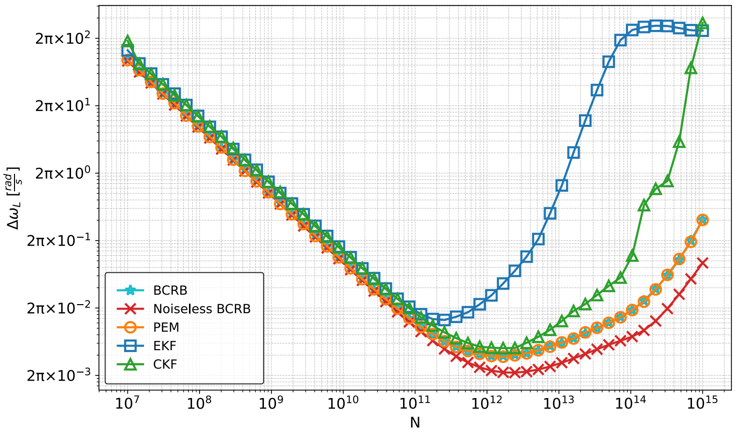


Figure 1: Estimation error as a function of the number of atoms for EKF, CKF and PEM, compared to the Bayesian Cramér-Rao Bound (BCRB), and the noiseless BCRB. The results demonstrate that PEM consistently tracks the CRB across all N, while the EKF and CKF achieve their optimal performance at some specific values of N. Futhermore, the CKF proves to be more suitable inference method than the EKF for larger number of atoms involved in experiment. The simulation was performed with the parameters experimental parameters consistent with [1].

References

[1] R. Jiménez-Martínez, J. Kołodyński, C. Troullinou, V. G. Lucivero, J. Kong, and M. W. Mitchell, Signal tracking beyond the time resolution of an atomic sensor by Kalman filtering, Phys. Rev. Lett. 120, 040503 (2018)

[2] S. Särkkä, Bayesian filtering and smoothing, Institute of Mathematical Statistics textbooks ; 3 (Cambridge University Press, Cambridge).

Quantum metrology with click-counting measurements

S. Eshete[1,2], T. Meier[1,2], P. Sharapova[1], and J. Sperling[1,2]

[1] *Department of Physics, Paderborn University, Warburger Str. 100, D-33098 Paderborn, Germany*
[2] *Institute for Photonic Systems (PhoQS), Paderborn University, Warburger Str. 100, D-33098 Paderborn, Germany*

Ideal NOON states constitute the optimal quantum states for phase estimations via Mach–Zehnder interferometers within the realms of quantum metrology and precision measurement. Their phase sensitivity is governed by the Heisenberg scaling in accordance with the mean photon number. The meticulous design of the associated scheme and the method of generation poses a significant challenge within the field of quantum metrology. Specifically, true photon-number resolution for the generation and detection is typically not available and may be replaced with click-counting devices, in practice. Therefore, in this work, we provide the theory for click-detection-based counterparts of NOON states and their interferometer propagation (polynomial decomposition of NOON states [1, 2]). In addition, the determination of quantum Fisher information through click-counting is derived, leading to minimal phase detection uncertainties below the Heisenberg limit. Also the fidelity of the click-NOON state to the ideal one is evaluated and shows a good approximation and correct limit as the number of measurable clicks increases.

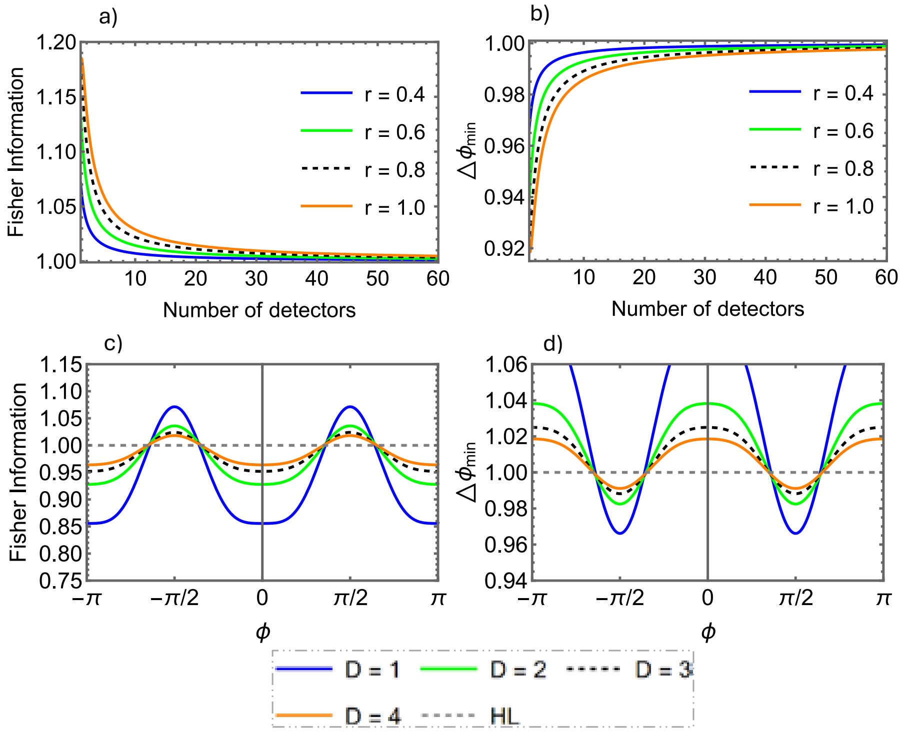


Figure 1: a) Fisher information as a function of the number of detectors D for different squeezing parameters r of the heralded source. b) Fisher information as a function of the interferometer phase for different numbers of detectors. c) minimum phase uncertainty against the number of detectors. d) minimum phase uncertainty against the phase of the interferometer. (HL: Heisenberg limit) All simulated figures are provided for 99.9% quantum efficiency to show click-resolution behavior rather than efficiency limitations.

References

[1] P. Kok, Opt. Spectrosc. **111**, 520 (2011).

[2] J. Yoshikawa, M. Bergmann, P. v. Loock, M. Fuwa, M. Okada, K. Takase, T. Toyama, K. Makino, S. Takeda, and A. Furusawa, Phys. Rev. A **97**, 053814 (2018).

Correlation plenoptic microscopy with entangled beams

D. Giannella[1,2], R. Vaira[1], G. Massaro[1,2], F. V. Pepe[1,2], M. D'Angelo[1,2]

[1]*Dipartimento Interateneo di Fisica, Università degli Studi di Bari Aldo Moro, Bari, 70126 Italy*
[2]*Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Bari, Bari, 70125 Italy*

Correlation plenoptic imaging (CPI) is a recently established light-field imaging technique enabling scanning free, high resolution, three-dimensional imaging and depth of field enhanced imaging [1, 2]. The peculiarity of CPI relies in retrieving the light-field, or *plenoptic information*, namely, the combined information about spatial details of the object and the direction of propagation of the light rays, exploiting the intensity correlations of the detected light, collected by two disjoint and synchronized high resolution detectors. For this measured second order correlation function to be rich in information, both chaotic and pseudo-chaotic light and entangled photons or beams of entangled photons can be employed [1, 2].

This way to retrieve the light field implies, as a direct consequence, a depth of field extension of the optical system, which is independent of its numerical aperture, as inherited by the properties of spatial coherence of light [3]; moreover, this extension does not sacrifice the diffraction limited resolution [4] and can be applied for refocusing out-of-focus planes of the sample and to reconstruct three-dimensional images.

In the past years, the application of CPI to the microscopy domain has been experimentally demonstrated in imaging bi-dimensional and three-dimensional targets and biomedical phantoms, only exploiting chaotic light [2].

Here we present the implementation of CPI oriented to microscopy in a setup exploiting beams of entangled photons produced from type-II spontaneous parametric down-conversion, operating in a regime of many photons per pixel per frame, aiming at investigating the possibilities to reduce CPI noise offered by quantum correlations in space/momenta, time and intensity.

We will present the optical architecture and an analysis of its resolution limits and optical performance, showing also the experimental refocusing of an out-of-focus bi-dimensional test target and the computational analysis tools employed to improve the signal-to-noise ratio of the refocused images.

An interesting feature that will also be discussed is how CPI can improve the signal-to-noise ratio of conventional ghost imaging, as shown in Fig. 1, as an intrinsic characteristic of the CPI measurement and analysis protocol.

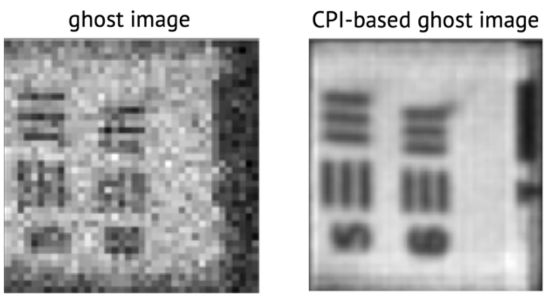


FIG. 1: Comparison between a ghost image and a CPI-based ghost image of a test target.

References

[1] F. V. Pepe, F. Di Lena, A. Garuccio, G. Scarcelli, and M. D'Angelo, *Correlation plenoptic imaging with entangled photons*, Technologies, **4**, no. 2, 17 (2016).

[2] G. Massaro, D. Giannella, A. Scagliola, F. Di Lena, G. Scarcelli, A. Garuccio, F. V. Pepe, and M. D'Angelo, *Light-field microscopy with correlated beams for high-resolution volumetric imaging*, Sci. Rep., **12**, no. 1, 16823 (2022).

[3] G. Massaro, B. Barile, G. Scarcelli, F. V. Pepe, G. P. Nicchia, M. D'Angelo, *Direct 3D Imaging through Spatial Coherence of Light*, Laser Photonics Rev, **18**, 2301155 (2024).

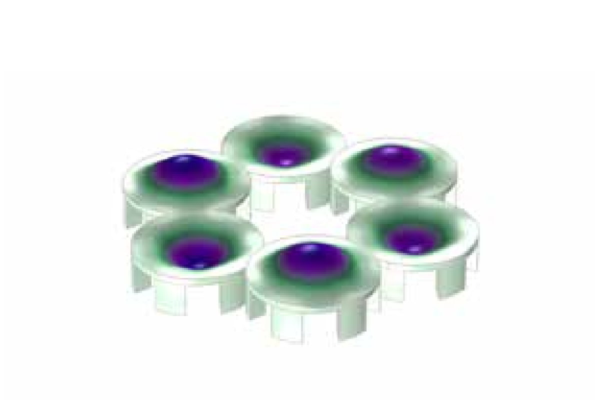
[4] G. Massaro, *Assessing the 3D resolution of refocused correlation plenoptic images using a general-purpose image quality estimator*, Eur. Phys. J. Plus, **139**, 727 (2024).

Direct Laser-Written Optomechanical Metamaterials in Optical Cavity Arrays

Florian Giefer[1], Daniel Stachanow[1], Lukas Tenbrake[1], Jana Blechmann[1], Benedikt Beck[1], Hannes Pfeifer[2] and Sebastian Hofferberth[1]

[1] *Institute of Applied Physics, University of Bonn, Bonn, Germany*
[2] *Department of Microtechnology and Nanoscience, Chalmers University of Technology, Gothenburg, Sweden*

Optomechanical platforms have diverse applications, reaching from quantum limited sensing to long-lived storage of quantum information [1]. The combination of mechanical systems with optical cavities provides an interface to boost optomechanical coupling through the repeated interaction between light and mechanics. Fiber Fabry-Perot cavities (FFPCs) [2] are of particular interest, because they open a path to easy integration and strong miniaturization by substituting conventional mirrors with Bragg reflector coated optical fibers [3]. Devices utilizing out-of-plane optical control over coupled mechanical resonators in an on-chip device layer [4] enable an unobstructed mechanical design compared to conventional MEMS devices. In this contribution the design and first experiments of a novel platform combining laterally coupled mechanical oscillators with fiber cavities is presented. To simultaneously interface several mechanical resonators we envisage utilizing a multicore fiber mirror. The cores allow simultaneous addressing of multiple optomechanical coupling sites. The mechanical system is constructed via direct laser writing utilizing two-photon absorption in a liquid polymer resin. We aim to demonstrate lateral oscillator coupling together with a multicore fiber interface. In the next step we aim to optimize the mechanical design and manufacturing parameters to achieve reliable mechanical circuits. That could allow for the creation of logical gates, which opens up a perspective for improved resilience and power efficiency of classical hardware and a functional interface for on-chip quantum technology.



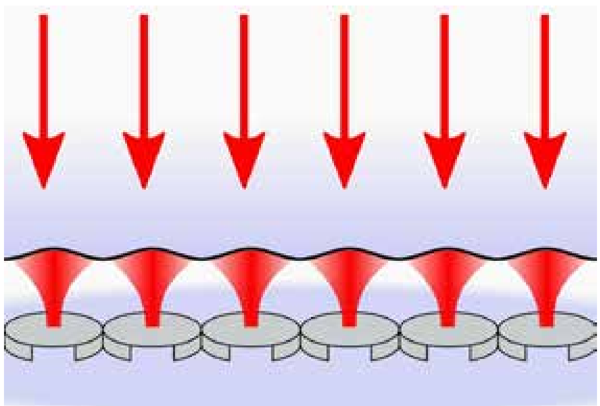


Figure 1: Example simulation of possible mechanical oscillator geometry (left). Visualization of the multicore fiber optomechanic interface (right).

[1] M. Aspelmeyer, *Cavity optomechanics* (Rev. Mod. Phys., 2014).

[2] H. Pfeifer, *Achievements and perspectives of optical fiber Fabry–Perot cavities* (Appl. Phys. B, 2022).

[3] L. Tenbrake, *Direct laser-written optomechanical membranes in fiber Fabry-Perot cavities* (Nat. Commun., 2024).

[4] T. Clark, *Optically Defined Phononic Crystal Defect* (Phys. Rev. Lett., 2024).

Resonant coupling in far-detuned two-level systems with permanent dipole moments

P. Gładysz[1,2], **A.V. Dodonov**[3,4]

[1] *Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, Grudziądzka 5, 87-100 Toruń, Poland*
[2] *Dipartimento Interateneo di Fisica, Università degli Studi di Bari, I-70126 Bari, Italy*
[3] *International Center of Physics, Institute of Physics, University of Brasilia, 70910-900, Brasilia, DF, Brazil*
[4] *Instituto de Física, Universidade de Brasília, Caixa Postal 04455, CEP 70910-900, Brasília, DF, Brazil*

In this study we investigate the interaction of classical electromagnetic fields with an asymmetric quantum system within the electric dipole approximation, focusing on the far-detuned regime.

The quantum system is modeled as two-level system with ground $|g\rangle$ and excited $|e\rangle$ states, separated by an energy gap $\hbar\omega_{eg}$. The dipole moment operator $\hat{d}$ gives rise to both the transition dipole moment $\vec{d}_{eg} = \langle e|\,\hat{d}\,|g\rangle$, commonly used in quantum optics, and a permanent dipole moments difference $\vec{d}_z = 1/2(\langle e|\,\hat{d}\,|e\rangle - \langle g|\,\hat{d}\,|g\rangle)$, which arises due to the system's asymmetry. In general, these two vectors are non-parallel and form an angle α, as shown in FIG. 1a.

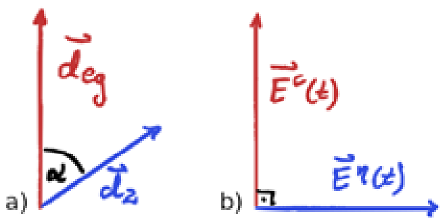


FIG. 1: a) Transition and permanent dipole moments configuration. b) Electric fields configuration.

The external electric field consisting of two perpendicular plane waves, $\vec{E}^c(t)$ and $\vec{E}^\eta(t)$ (FIG. 1b), is given by

$$\vec{E}(t) = \underbrace{E_0^c \vec{e}_c \cos(\omega_c t)}_{\vec{E}^c(t)} + \underbrace{E_0^\eta \vec{e}_\eta \cos(\eta t)}_{\vec{E}^\eta(t)},$$

where $\vec{e}_{c,\eta}$ are polarization unit vectors. The field $\vec{E}^c(t)$ drives transitions between $|g\rangle$ and $|e\rangle$, aligning with transition dipole moment $\vec{d}_{eg}||\vec{e}_c$, while $\vec{E}^\eta(t)$ couples to the permanent dipole moment difference.

For $\alpha \approx \pi/2$, the interaction term $\vec{E}^c(t) \cdot \vec{d}_z$ is negligible, and the total Hamiltonian simplifies to

$$\hat{H}(t) = \frac{1}{2}\big(\hbar\omega_{eg} + E_0^\eta d_z \sin\alpha \cos(\eta t)\big)\hat{\sigma}_z + E_0^c d_{eg} \cos(\omega_c t)\hat{\sigma}_x, \quad (1)$$

where $\hat{\sigma}_{z,x}$ are Pauli matrices. This form clearly separates the longitudinal ($\hat{\sigma}_z$) and transverse ($\hat{\sigma}_x$) couplings, with $\vec{E}^\eta(t)$ inducing oscillations of the energy levels at frequency η, while population transitions remain controlled by ω_c. This additional degree of freedom enables resonant behavior in a highly off-resonant regime, where $\omega_c/\omega_{eg} \in (0, 0.5)$, and for weak energy level oscillation $E_0^\eta d_z/\hbar\omega_{eg} \in (0, 0.1)$.

However, due to the spectrally narrow nature of this resonance, precise tuning of the frequency η based on the system's parameters is required. The impact of the permanent dipole moments and driving field's intensity on the energy gap and coupling strength has to be taken into account. We achieve that by applying a series of unitary transformations to Eq. (1). As a result, we determine the value of η at which resonance occurs, and obtain a time-independent, Jaynes-Cummings-like form of the Hamiltonian, allowing for an analytically solvable evolution.

The introduced mechanism provides a novel approach to quantum control *via* longitudinal modulation, and is a continuation of the previous work examining interaction with a single plane wave [1-3].

References

[1] Gładysz, P., Wcisło, P., & Słowik, K. (2020). Propagation of optically tunable coherent radiation in a gas of polar molecules. Scientific reports, 10(1), 17615.

[2] Izadshenas, S., Gładysz, P., & Słowik, K. (2023). Hybrid graphene-silver nanoantenna to control THz emission from polar quantum systems. Optics Express, 31(18), 29037-29050.

[3] Gładysz, P., & Słowik, K. (2024). Rabi frequency for polar systems interacting with light. arXiv preprint arXiv:2408.13011.

Quantum Metrology under Coarse-Grained Measurement

Byeong-Yoon Go[1], Geunhee Gwak[1], Young-Do Yoon[1], Nicolas Treps[2], Jiyong Park[3], Young-Sik Ra[1]

[1]*Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon, 34141, Korea*
[2]*Laboratoire Kastler Brossel, Sorbonne Université, ENS-Université PSL, CNRS, Collège de France, 4 place Jussieu, F-75252 Paris, France*
[3]*School of Basic Sciences, Hanbat National University, Daejeon 34158, Korea*

The squeezed light is a key resource for various continuous-variable quantum technologies, offering noise reduction that enhances sensitivity in quantum metrology [**1**, **2**]. While most studies on quantum phase estimation assume ideal, fine-grained detectors, realistic experiments inevitably involve coarse-graining due to limited measurement resolution, and the effect of coarse-graining in quantum information tasks can be nontrivial [**3**]. Therefore, it is necessary to investigate the impact of coarse-graining effects on the phase sensitivity in the quantum phase sensing schemes. In this work, we build an experimental interferometry setup as Fig. 1 to investigate quantum phase sensing using squeezed light under coarse-grained measurement. Moreover, we identify optimal bin configurations and estimation strategies that minimize phase error for a given number of bins.

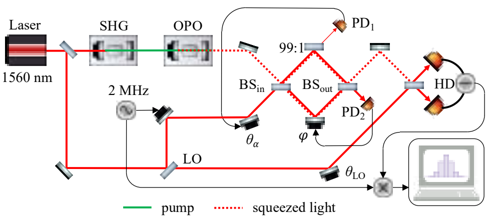


Figure 1: Experimental setup

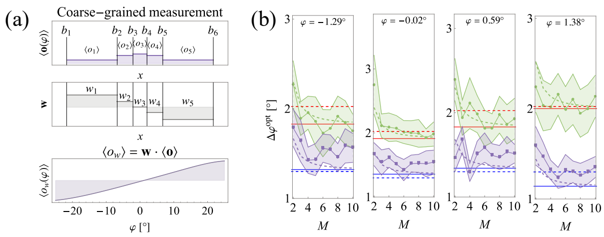


Figure 2: Experimental results

Fig. 2(a) illustrates key steps for constructing the phase calibration function. First, we numerically determine the bin boundaries b_k, where $k \in \{1, \cdots, M+1\}$ and M is the total number of bins, which maximize the classical Fisher information at the optimal phase condition. The expectation value of single measurement outcome in k^{th} bin $\langle o_k \rangle$ is obtained by counting the quadrature outcomes between b_k to b_{k+1}, as shown in the top panel for $M = 5$. Here, we define the phase calibration function as $\langle o_w \rangle \equiv \mathbf{w} \cdot \langle \mathbf{o} \rangle$, where $\mathbf{w}$ is the optimal weight vector obtained via the *method of moments*, such that the phase sensitivity saturates the Cramér–Rao bound at the optimal phase. The experimentally calibrated optimal weight vector and the resulting phase calibration function for $M = 5$ are shown in the second and bottom panels, respectively.

Fig. 2(b) shows the experimentally obtained phase error at 9 phase points near the optimal phase. The purple and green dots represent the phase error under coarse-grained measurement as a function of bin number M, with and without squeezing, respectively. Also, the dashed lines with the corresponding colors show their theoretical predictions. The red and blue lines indicate the phase error of ideal measurement with and without squeezing, respectively. Here, we observed 3.8 dB enhanced sensitivity with squeezed light across all coarse-grained measurements. Remarkably, for some phase points, the phase error with squeezed light under coarse-grained measurement remains consistently lower than that without squeezing under ideal measurement, regardless of the bin number M. These results highlight the robustness of our strategy in quantum-enhanced phase sensing against coarse-grained measurements, surpassing classical phase estimation limits.

References

[1] C. M. Caves, "Quantum-mechanical noise in an interferometer" Phys. Rev. D **23**, 1693 (1981).

[2] J. A. H. Nielsen, J. S. Neergaard-Nielsen, T. Gehring, and U. L. Andersen, "Deterministic quantum phase estimation beyond NOON state", Phys. Rev. Lett. **130**, 123603 (2021).

[3] C. Roh, Y.-D. Yoon, J. Park, and Y.-S. Ra, "Continuous-variable nonclassicality certification under coarse-grained measurement" Phys. Rev. Res. **5**, 043057 (2023).

Squeezed Lasing via Cavity-Assisted Raman Transitions

Rodrigo Grande de Diego[1], **Carlos Sánchez Muñoz**[2]

[1,2] *Instituto de Física Fundamental IFF-CSIC, Calle Serrano 113b, 28006 Madrid, Spain*

A squeezed laser [1] is a system in which a squeezed cavity mode acquires a macroscopic photonic occupation through stimulated emission. Above the lasing threshold, the emitted light maintains both the spectral purity of a conventional laser and the quadrature-squeezing characteristics of correlated photons. Here, we propose an implementation of such a device in the optical regime by leveraging cavity-assisted Raman transitions in multi-level atoms—an approach previously suggested for simulating the Dicke model. Crucially, we demonstrate that the intricate interplay between dissipation and high-energy virtual states involved in Raman processes leads to a complex driven-dissipative phase transition, whereby a transient metastable lasing phase can emerge, which eventually breaks down in the long-time limit due to unconventional mechanisms of population of the virtual states [2]. However, we show that careful engineering of dissipation channels can restore steady-state squeezed lasing. These findings establish this system as a compelling platform for exploring the fundamental physics of dissipative phase transitions, quantum simulation in non-equilibrium environments, and potential applications in quantum metrology.

References

[1] C. S. Muñoz and D. Jaksch, Squeezed lasing, Phys. Rev. Lett. **127**, 183603 (2021)

[2] A. Vivas-Viaña, A. González-Tudela, and C. S. Muñoz, Unconventional mechanism of virtual-state population through dissipation, Phys.Rev. A **106**, 012217 (2022)

Optical System for Bi-Directional Tracking in Free-Space Quantum Key Distribution Link

Akhil Gupta[1,4], Manpreet Kaur[1,3,4], Michael Auer[1,2,4], Michael Steinberger[1,4], Adomas Baliuka[1,4], Moritz Birkhold[1,4], Harald Weinfurter[1,3,4], Lukas Knips[1,3,4]

[1] *Ludwig Maximilian University of Munich, Munich, Germany*
[2] *Universität der Bundeswehr München, Munich, Germany*
[3] *Max Planck Institute of Quantum Optics, Garching, Germany*
[4] *Munich Center for Quantum Science and Technology, Munich, Germany*

Quantum Key Distribution (QKD) offers a fundamentally secure method for generating shared secret keys by leveraging the principles of quantum mechanics. Unlike conventional cryptographic protocols that rely on the assumed hardness of mathematical problems, QKD provides security by ensuring that any eavesdropping attempt introduces detectable disturbances. With appropriate post-processing techniques such as error correction and privacy amplification, any information potentially leaked to the eavesdropper can be effectively erased, guaranteeing the integrity and secrecy of the final key.

Compared to fiber-based systems, free-space QKD presents unique advantages, particularly in terms of deployment flexibility. The implementation of Free-space QKD allows significantly compact, cost-effective, and rapidly deployable systems, making them ideal candidates for satellite-to-ground and ground-to-ground links[**1**] where fiber laying is impractical.

This work focuses on the development of a ground-to-ground free-space QKD link designed to demonstrate efficient key exchange over a 3-kilometer distance using compact and portable hardware. At the heart of the system is a custom-designed symmetrical telescope setup. The QKD sender module is coupled using a single-mode fiber to the telescope, which transmits quantum signals, i.e., weak coherent pulses, through turbulent atmosphere. At the receiving end, the telescope collects the signal and couples it to the receiver QKD module via a single-mode fiber.

Here we present the design of a telescope system engineered to minimize wavefront distortion, ensuring high coupling efficiency. The system operates at two wavelengths: 850 nm for quantum signal transmission and 1550 nm for classical beacon signals used for tracking, synchronization, and control. Therefore, the proposed dual-wavelength approach ensures robust, real-time alignment and enhances system reliability in the presence of atmospheric perturbations[**2**], primarily angle of arrival fluctuations.

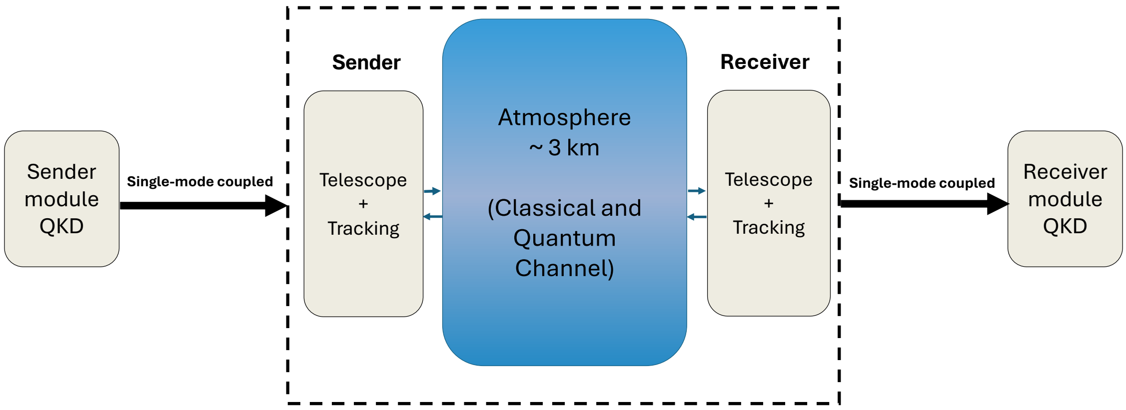


Figure 1: Bi-Directional Free-Space Link

References

[1] R. Ursin *et al.*, Nat. Phys. **3**, 481 (2007).

[2] L. C. Andrews, Opt. Sensors Sens. Congr., PM1D.6 (2020).

State Transfer in Noisy Modular Quantum Networks

Markku Hahto[1], Jyrki Piilo[1], Johannes Nokkala[1]

[1] *Department of Physics and Astronomy, University of Turku, Turku, Finland.*

Complex quantum networks cover diverse fields of physics and have raised a large interest in the recent years [**1**]. Within this framework one can consider quantum state transfer, which is the act of transferring quantum information from one system to another without physically transporting carriers of quantum information. Instead, the transfer is mediated by a network of interacting quantum systems, such as spins [**2**] or harmonic oscillators [**3**], whose Hamiltonian is engineered such that the state of the sender is transferred to the receiver through the dynamics of the whole network. A generalization of quantum state transfer called quantum routing concerns simultaneous transfers between multiple pairs of nodes in a quantum network. This imposes limitations on the network structure, and for example modular networks have been identified as a suitable platform for routing [**4**].

In this study we consider the transfer of Gaussian states over noisy modular networks of quantum harmonic oscillators [**5**]. We compare two noise models, affecting either the network topology or the frequencies of the network oscillators, and study their effects on the transfer fidelities and the network properties. The two models are found to affect different features of the network, allowing for the identification and quantification of the noise. These features are then used as a guide toward strategies for the compensation of the noise. Our results show that, in general, modular networks are more robust to noise than monolithic ones.

References

[1] J. Nokkala, J. Piilo, G. Bianconi. Complex quantum networks: a topical review. *J. Phys. A: Math. Theor.* **57** 233001 (2024)

[2] S. Bose, *Phys. Rev. Lett.* **91**, 207901 (2003)

[3] M. B. Plenio, J. Hartley, J. Eisert. *New J. Phys.* **6**, 36 (2004)

[4] M. Hahto, J. Nokkala, G. García-Pérez, S. Maniscalco, J. Piilo. *arXiv preprint* arXiv:2403.05623. (2024).

[5] M. Hahto, J. Piilo, J. Nokkala. *Adv Quantum Technol.* **8**, 2400316 (2025).

Matched optical vortices of slow light using a tripod coherently prepared scheme

Hamid R. Hamedi[1], **Ite A. Yu**[2,3], **Emmanuel Paspalakis**[4]

[1] *Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio 3, Vilnius LT-10257, Lithuania*
[2] *Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan*
[3] *Center for Quantum Science and Technology, National Tsing Hua University, Hsinchu 30013, Taiwan*
[3] *Materials Science Department, School of Natural Sciences, University of Patras, Patras 265 04, Greece*

We study the propagation of optical vortices of slow light inside a four-level tripod atomic light-matter coupling system (Fig. 1). Initially, the system is prepared in a coherent superposition of two out of the three lower levels by, for example, coherent population trapping, while the third lower state remains unoccupied. The unoccupied state is coupled to a strong control laser field with a constant Rabi frequency, lacking orbital angular momentum (OAM). Simultaneously, one of the remaining lower states interacts with a weak vortex beam. The third lower state has no initial coupling to any field. This arrangement effectively closes the level transitions, resulting in a phase-dependent configuration.

By solving the Maxwell-Schrödinger equations, we provide analytical evidence that the application of a strong control field can generate an additional optical vortex of slow light. This vortex possesses the same OAM as the incident vortex beam. Furthermore, we explore the matching of optical vortices at different propagation distances, contingent upon the intensity of the control field [1].

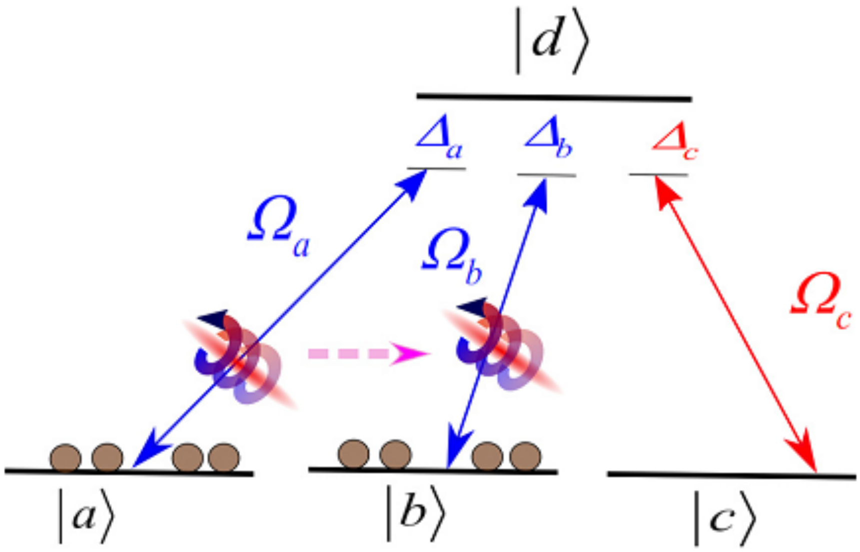


Figure 1: The level structure of a four-level atom-light coupling schemewithatripodconfiguration.

References

[1] Hamid R. Hamedi, Ite A. Yu, and Emmanuel Paspalakis, Phys. Rev. A **108**, 053719 (2023).

Towards interfacing quantum states from an airborne WGMR with Yb ions in a ground-based ion trap

Sheng-Hsuan Huang[1,2], Thomas Dirmeier[1,2], Martin Fischer[1,2], Sebastian Luff[1,2], Hans Dang[1,2], Markus Sondermann[1,2], Gerd Leuchs[1,2], and Christoph Marquardt[2,1]

[1]*Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany*
[2]*Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstr. 7, 91058 Erlangen, Germany*

The implementation of efficient long-range quantum networks requires interconnecting quantum memories in different locations. Quantum memories are often envisioned to be built from atomic systems as they promise faithful storage, processing, and read-out of quantum information [1]. A way to interconnect such quantum memories is via photons. This requires narrowband photon sources that can efficiently interact with atomic systems and transmit information via optical communication channels. As part of the German QuNET initiative, it is our goal to demonstrate technical key aspects when interfacing a stationary ion trap with a mobile source of narrowband quantum states located on an airplane. In our system, we generate narrowband quantum states via spontaneous parametric downconversion from a Whispering Gallery Mode Resonator (WGMR). This type of source has proven to be a compact, efficient, single mode source of quantum states, and compatible with alkali metal vapors [2-4]. In this experiment, we utilize a WGMR made from 5% MgO-doped z-cut lithium niobate as source of heralded single photons. The bandwidth of the signal is about 11MHz and the signal's frequency is tuned to the D3/2 ⇔ D[3/2]1/2 transition of 174Yb+ ions at 935 nm. We check photon-ion interaction by measuring scattered photons from the ion as follows: When the ion interacts with a photon, it is excited from the D3/2 state into the D[3/2]1/2 state that decays into the S1/2 ground state with a probability of 98% . We can then use a laser at 370 nm to scatter photons on the S1/2 – P1/2 transition verifying the absorption of a 935 nm photon. The recorded photon number histograms of the scattered 370 nm photons thus serve as a witness for the successful photon-ion interaction. We define events with more than 4 scattered photons as successful interactions and calculate the success rate. The result shows that the success rate is 8.1%. In the presentation, we highlight our results on interfacing light generated in a WGMR to an Yb ion trapped in a deep parabolic mirror [5]. We will furthermore discuss the challenges faced when miniaturizing a WGMR source for use in aerospace environment and discuss our measures to compensate for the drifts induced by this highly dynamic environment.

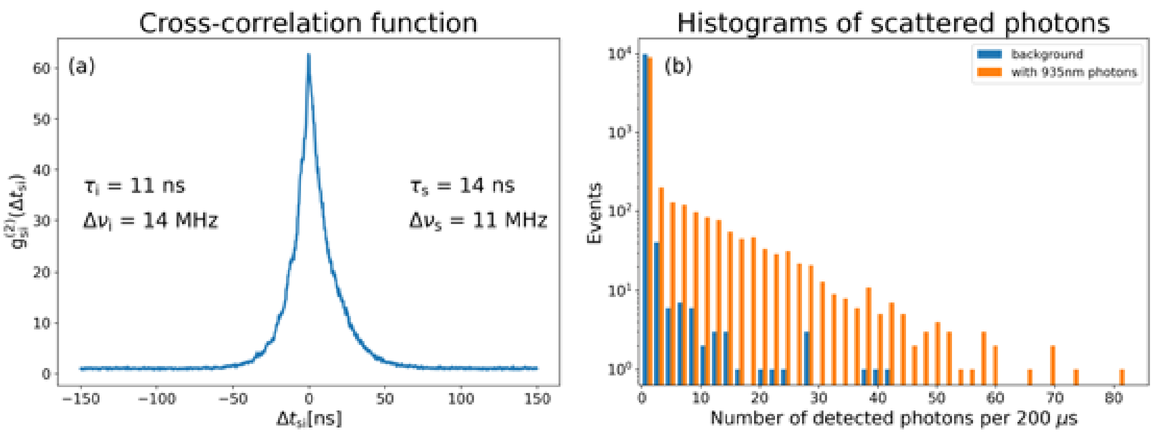


FIG. 1: Experimental results. (a) is the Glauber second-order correlation function between the signal and idler generated from the WGMR. The bandwidths of the signals and idlers are 11 MHz and 14 MHz, respectively. (b) Photon number histograms of scattered 370nm photons with and without 935nm photons. The count rate of the 935 nm photons is 2M cps and the detection window is 200 μs, meaning that about 280 photons per cycle may interact with the ion. We make 10,000 measurements each. For the background measurement, we have a 0.035% chance of having an event with more than 4 scattered photons. For the measurement with 935nm photons, the chance is 8.1%.

References

[1] N. Sangouard, et.al., Rev. Mod. Phys. 83 33–80 (2011)
[2] G. Schunk, et.al., Journal of Modern Optics 63 (2016)
[3] M. Förtsch, et,al., Phys. Rev. A. 91(2) 023812 (2015)
[4] S-H. Huang, et.al., npj Quantum Information 10.1 (2024)
[5] R. Maiwald, et.al., Phys. Rev. A. 86, 043431 (2012)

Optical Time-Domain Quantum State Tomography on a Subcycle Scale

E. Hubenschmid[1], **G. Burkard**[1]

[1] *University of Konstanz*

Electro-optic sampling presents a powerful tool to sample the waveform of a free space mid-infrared pulse in the time domain by measuring the effect a nonlinear interaction of the sampled mid-infrared pulse has on an ultra-short near-infrared pulse. Recent experiments applied this technique to sample the electric field fluctuation of the squeezed vacuum on a subcycle scale. However, a full quantum tomography scheme in the time domain is still missing. Here we present a theoretical description of a (time local) quantum tomography scheme with subcycle resolution [1]. Furthermore, we demonstrate that some states exhibit (quantum) correlations in the time domain which limit the access to the full quantum state together with its dynamics. By extending the previously time local measurement to include temporal correlations our proposed tomography scheme is able to fully reconstruct a quantum state together with its dynamics, as long as the Wigner function of the state is Gaussian. We support our analysis by devising a notion of entanglement in the time domain based on a quantum information theoretical approach, which is experimentally verifiable by our proposed setup.

References

[1] E. Hubenschmid, Phys. Rev. X **14**, 041032 (2024).

Probing New Physics with Calcium Isotope Shift Measurements using a Trapped Ion Quantum Computing Platform

Luca I. Huber

Institute for Quantum Electronics, Department of Physics, Eidgenössische Technische Hochschule Zürich, Otto-Stern-Weg 1, 8093 Zurich, Switzerland

Luca I. Huber[1], Gabriele J. Giuli[1], Jeremy Flannery[1], Roland Matt[1], Martin Stadler[1], Robin Oswald[1], Fabian Schmid[1], Daniel Kienzler[1], Diana P.L. Aude Craik[1], Jonathan Home[1]

[1]*Institute for Quantum Electronics, Department of Physics, Eidgenössische Technische Hochschule Zürich, Otto-Stern-Weg 1, 8093 Zurich, Switzerland*

Precision metrology provides a compelling avenue to test physics beyond the Standard Model through isotope shift measurements. In our previous work, we employed correlation spectroscopy on co-trapped pairs of Ca^+ ions to measure the isotope shift of the $S_{1/2} \rightarrow D_{5/2}$ transition with sub-Hz precision. Using a technique called King plot analysis and combining these results with isotope shift measurements in Ca^{14+} at PTB Braunschweig and more precise measurements of the nuclear mass ratios at MPIK Heidelberg allowed to establish bounds on a hypothetical boson mediating a force between neutrons and electrons [1]. However, these bounds are limited by the theoretical uncertainty related to nuclear polarization.

In our most recent study, we extend the previous results by measuring the $S_{1/2} \rightarrow D_{3/2}$ transition in Ca^+ while leveraging entanglement between the pair of co-trapped ions to achieve a projected precision at the 10 mHz level. With this additional set of measurements, we aim to mitigate the impact of nuclear polarization uncertainties, increasing our sensitivity to beyond-Standard Model interactions. We anticipate that these measurements will significantly tighten the constraints on the interaction strength of such a boson compared to previous isotope shift measurements. Moreover, this work demonstrates how techniques developed for quantum computing — such as single qubit control and entanglement — can be harnessed to achieve state-of-the-art precision metrology.

References

[1] A. Wilzewski, L. I. Huber, M. Door, J. Richter, A. Mariotti et al., arXiv:2412.10277 (2024)

Laser-Induced Fluorescent Defects in Hexagonal Boron Nitride

J. Janušonis, **V. Šilys, I. Bibi,**
E. Markauskas, T. Paulauskas

Center for Physical Sciences and Technology, Vilnius

Hexagonal boron nitride (hBN) is a 2D material hosting a wide variety of fluorescent quantum defects which have become a topic of intense research efforts in the last few years [1-4]. The defects either occur naturally during the material growth, or can be created via ion implantation [5], electron beam [6,7], or laser irradiation [8]. While the paramagnetic properties of reported defects do not compare favorably with other systems, such as NV center in diamond, high room-temperature fluorescence yields, short fluorescence decay times (of an order of ~1-3ns) [9], and narrow spectral lines are qualities that make them attractive as single-photon emitters.

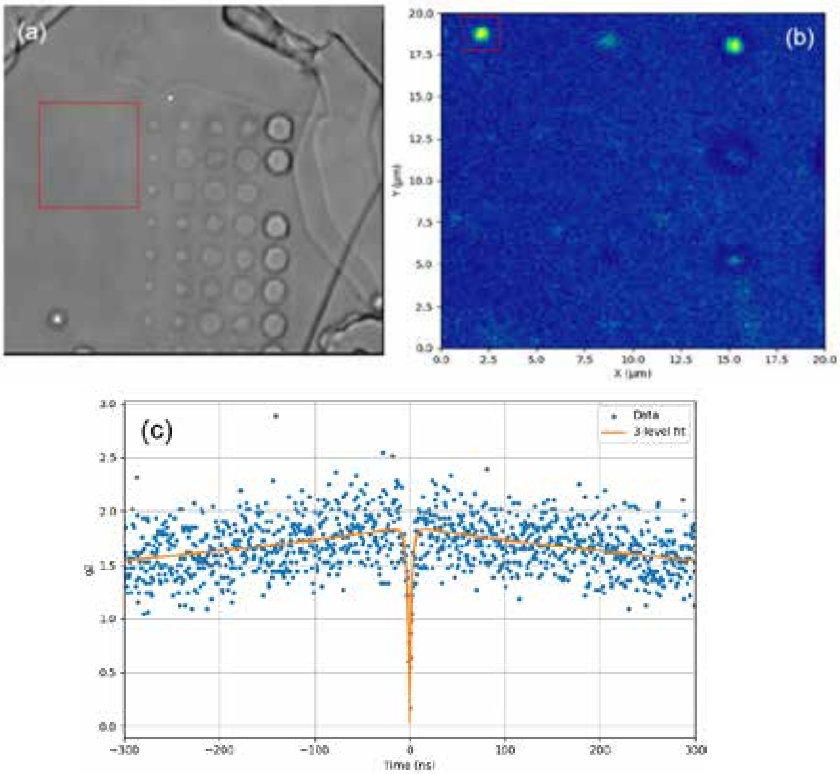


FIG. 1: Laser-induced defects in hBN: (a) a matrix of laser-exposed sites; pulse energy increases from left to right, (b) fluorescence intensity of the highlighted area, (c) two-photon correlation function of a single laser-induced defect.

In this work we investigate fluorescent defect creation in multilayer hBN by illumination with ultrashort laser pulses to induce defects at desired locations (Fig. 1). Both multiple and single fluorescent defects are created this way, and here we report their characterization results.

References

[1] T.T. Tran et al., *Nature nanotechnology* 11.1 (2016): 37-41.

[2] I. Aharonovich, et al., *Nano Letters* 22.23 (2022): 9227-9235.

[3] Turiansky, M. E., et al., *Nature Materials* 19 (2020), 487–489

[4] Maciaszek, M.; Razinkovas, L., *ACS Appl. Nano Mater.* 7.16 (2024), 18979–18985

[5] G.L. Liu, et al., *Advanced Optical Materials* 12.9 (2024): 2302083.

Entanglement detection in high-dimensional states via Hilbert space mapping

J. Kadlec[1,2], A. Barasinski[3], K. Lemr[2]

[1] Institute of Physics of the Academy of Sciences of the Czech Republic, Joint Laboratory of Optics of Palacký University and Institute of Physics AS CR, 17. listopadu 50a, 772 07 Olomouc, Czech Republic
[2] Palacký University in Olomouc, Faculty of Science, Joint Laboratory of Optics of Palacký University and Institute of Physics AS CR, 17. listopadu 12, 771 46 Olomouc, Czech Republic
[3] Institute of Theoretical Physics, University of Wroclaw, Plac Maxa Borna 9, 50-204 Wroclaw, Poland

This work proposes an entanglement detection method for high-dimensional bipartite systems. The procedure operates by mapping the high-dimensional Hilbert space onto a 2x2-dimensional space so that the portfolio of two-qubit entanglement detection methods can be used, for instance the fully entangled fraction. The proposed method is perfectly specific, i.e. never misclassifies a separable state, while maintaining a solid sensitivity. When performed optimally, it provides nearly perfect sensitivity for quasi-pure states. Moreover, the number of measurement configurations does not scale with the system dimension. We document effectiveness of our method on several classes of prominent states including states intractable by previously proposed protocols.

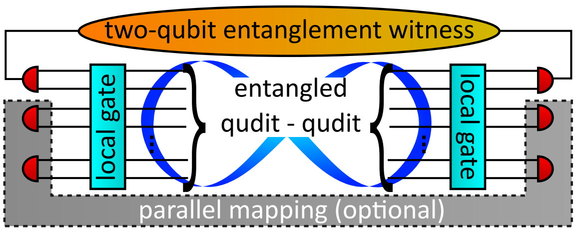


FIG. 1: Conceptual diagram of the proposed method. A two-qudit state is first subjected to a pair of local gates and then mapped onto the space of a two-qubit state. Standardizes two-qubit entanglement witnesses can subsequently be used. To increase detection efficiency further, one can map the two-qudit space onto several two-qubit states detecting entanglement in them in parallel.

Our method allows to build upon already established formalism to evaluate the entanglement of a higher-dimensional system while requiring relatively low number of measurements settings compared to the full two-qudit tomography. The method requires a two-qudit state $\rho_{AB}^{d\times d}$, which is subjected to a local unitary transformation $(U_A^d \otimes V_B^d)$, therefore not affecting the degree of entanglement. Subsequently, two level subsystem is chosen for each party $a \subset A \quad \dim(a) = 2$, $b \subset B \quad \dim(b) = 2$, by which the system is reduced to a two-qubit state and the procedure developed for the two-qubits is employed. In a case, where the entanglement is not witnessed, it is possible to reiterate this procedure using either different set of unitaries and/or different combination of levels. Using two distinct classes of states, we show, that high success rate can be achieved from three iterations regardless of the dimension.

Photon Counting Statistics in Gaussian Bosonic Networks

Kalle S. U. Kansanen[1,2], **P. Portugal**[2], **C. Flindt**[2,3], **P. Samuelsson**[1]

[1] *Department of Physics and NanoLund, Lund University, 22100 Lund, Sweden*
[2] *Department of Applied Physics, Aalto University, 00076 Aalto, Finland*
[3] *RIKEN Center for Quantum Computing, Wakoshi, Saitama 351-0198, Japan*

The statistics of transmitted photons in microwave cavities play a foundational role in microwave quantum optics and its technological applications. By utilizing quantum mechanical phase-space methods, we have developed a general theory of the photon counting statistics in Gaussian bosonic networks consisting of driven cavities with beamsplitter interactions and two-mode-squeezing [1, 2]. The dynamics of the network can be captured by a Lyapunov equation for the covariance matrix of the cavity fields, which generalizes to a Riccati equation, when counting fields are included. By solving the Riccati equation, we obtain the statistics of emitted and absorbed photons as well as the time-dependent correlations encoded in waiting time distributions and second-order coherence functions. We discuss the application of the theory to witnessing bipartite entanglement between cavity modes with only emitted photons, and to a three-mode bosonic circulator which can direct the flow of photons depending on the couplings between cavities.

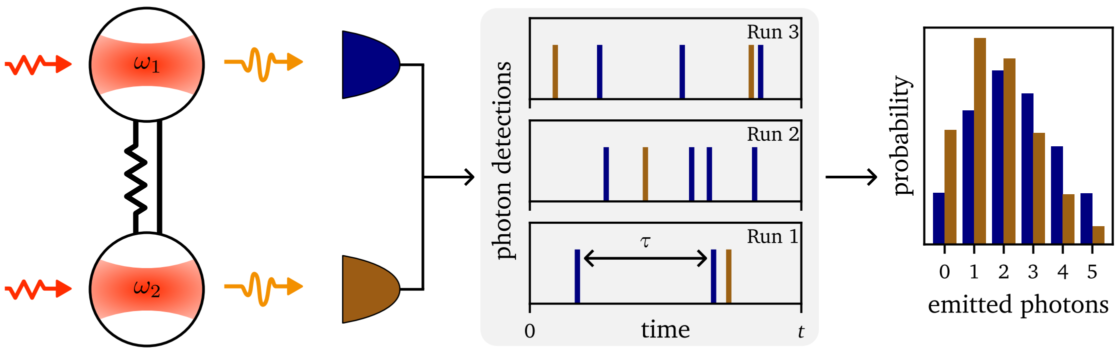


FIG. 1: Schematic idea of photon counting statistics. The coupled cavities (of eigenfrequencies $\omega_{1,2}$) absorb photons from their environment which are then emitted. In the time span $[0, t]$, random amounts of photons are detected, a distribution of which is described by our approach if the state of the cavity fields is Gaussian. Furthermore, we connect this description to temporal correlations of photon emissions. (Adapted from Ref. [1].)

References

[1] K. S. U. Kansanen, P. Portugal, C. Flindt, and P. Samuelsson, SciPost Phys., *in press*.

[2] P. Portugal, F. Brange, K. S. U. Kansanen, P. Samuelsson, and C. Flindt, Phys. Rev. Res. **5**, 033091 (2023).

Quantum Synchronizing Words: Resetting and Preparing Qutrit States

A. Grudka[1], **M. Karczewski**[1], **P. Kurzyński**[1], **J. Stempin**[1], **J. Wójcik**[1], **A. Wójcik**[1]

[1] *Institute of Spintronics and Quantum Information, Faculty of Physics and Astronomy, Adam Mickiewicz University, 61-614 Pozna'n, Poland*

Synchronizing words in classical automata theory provide a mechanism to reset any state of a deterministic automaton to a specific target state via a carefully chosen finite sequence of transition rules. In this work, we extend the concept of synchronizing words to quantum information theory. Specifically, we show that with only two quantum channels, it is possible to bring an arbitrary qutrit state close to a designated target state. Furthermore, we demonstrate that following this reset, any pure real qutrit state can be closely approximated using the same two channels. These findings establish a quantum analogue of synchronizing words, highlighting their potential applications in constructing minimal sets of universal quantum gates capable of both resetting and preparing arbitrary states.

References

[1] A. Grudka et al., arXiv:2502.09522.

Exploiting separation-dependent coherence to boost optical resolution

I. Karuseichyk[1], G. Sorelli[2], V.Shatokhin[3,4], M. Walschaers[1], N.Treps[1]

[1] *Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, 4 place Jussieu, F-75252 Paris, France*

[2] *Fraunhofer IOSB, Ettlingen, Fraunhofer Institute of Optronics, System Technologies and Image Exploitation, Gutleuthausstr. 1, 76275 Ettlingen, Germany*

[3] *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany*

[4] *EUCOR Centre for Quantum Science and Quantum Computing, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany*

The problem of resolving two optical point sources is of fundamental importance in quantum metrology and has numerous practical applications in areas ranging from astronomy to microscopy. The question about the role of the sources' mutual coherence gained a lot of attention recently. This problem is particularly interesting to study for the case of separation-dependent mutual coherence. In this work, we demonstrate that such dependence can significantly enhance resolution, providing practical examples to illustrate this effect.

We investigate the sensitivity of the spatial mode demultiplexing (SPADE) technique, which involves decomposing light into specific spatial modes prior to detection. This approach has proven to extract all relevant information about the separation between incoherent emitters when the measurement modes are chosen symmetrically relative to the centroid between the sources [1]. We extend this technique to estimate the separation between interacting dipoles, where the separation-dependent emission characteristics arising from emitter interactions can substantially enhance the sensitivity. Consequently, it becomes possible to extract valuable information about the dipole separation over timescales much longer than the radiative lifetime of the dipole's excited state. In the later stages of decay, despite the low probability of photon detection, the information gained from a detection event is significantly enhanced due to strong interaction-induced correlations between emitters. Notably, this effect is robust against both emitter dephasing and detection noise, making it a promising approach for high-sensitivity measurements [2].

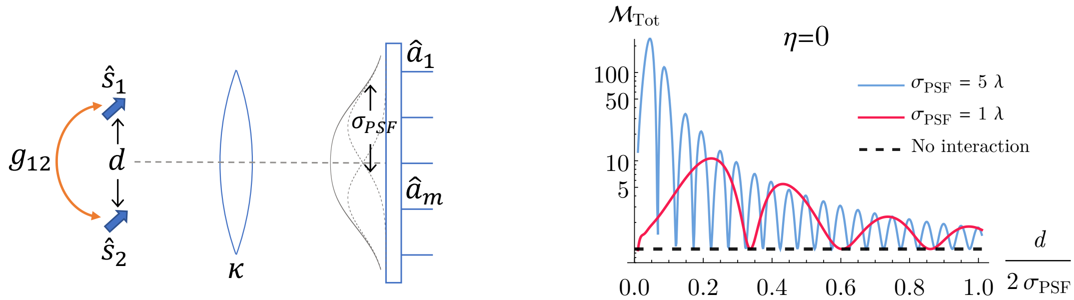


FIG. 1: (Left) Schematic representation of resolving two interacting emitters separated by distance d. The sources emit light into orthogonal modes $\hat{s}_{1,2}$, which propagate through a lossy imaging system characterized by transmissivity κ and point spread function (PSF) width σ_{PSF}, before being decomposed into spatial modes with corresponding field operators $\hat{a}_m$ and subsequently detected. (Right) Sensitivity of separation estimation based on SPADE tenchique. Different colors represent varying ratios of wavelength to PSF width, dashed line corresponds to incoherent emitters.

References

[1] J. Rehacek, et al. "Optimal measurements for resolution beyond the Rayleigh limit." Optics letters 42.2 (2017): 231-234.

[2] I. Karuseichyk et al. "Exploiting separation-dependent coherence to boost optical resolution." Physical Review A 109.4 (2024): 043524.

Multiplexed single-photon sources based on spatial multiplexers with optimized structure

A. Kaszas[1], M. Mechler[2,3], P.Adam[2,3]

[1] *Institute of Smart Technology and Engineering, University of Pécs, H-7624 Pécs, Boszorkány út 2.*
[2] *Institute of Physics, University of Pécs, H-7624 Pécs, Ifjúság útja 6.*
[3] *Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, P.O. Box 49, H-1525 Budapest, Hungary*

Single-photon sources still play an essential role in several experiments aiming at realizing or verifying theoretically established concepts in the fields of quantum information processing and photonic quantum technology. A possible realization of a single-photon source involves some kind of multiplexing of heralded single-photon sources where the multiphoton contribution in the individual heralded sources is suppressed by decreasing the input photon number, and the resulting increased zero-photon probability is reduced by the parallel use of several sources. Several theoretical and experimental studies have discussed the possible means to increase the single-photon probability of spatially, temporally or spectrally multiplexed sources [1, 2]. Using the statistical theory of these sources, it becomes possible to optimize multiplexed single-photon sources, that is, to maximize the output single-photon probability by determining the optimal system size, in other words, the number of multiplexed units, and the mean number of photon pairs generated in the multiplexed units for a given set of loss parameters [3–6]. Recently, in order to increase the single-photon probability of spatially multiplexed single-photon sources, the idea of optimizing the structure of the multiplexer has been raised. In Ref. [7] a method for the stepwise optimization of the structure of binary-tree multiplexers was developed. Then a method for finding the multiplexer with the optimal structure out of all possible structures formed by a given number of photon routers was proposed and analyzed for suboptimal numbers of the multiplexed units up to $N = 11$ [8]. This method basically scales with the factorial of the number of the constituent photon routers, hence finding the optimal number of the multiplexed units for a given set of the loss parameters is an intriguing issue.

In the present work, we accomplish the full optimization problem for several sets of realistic loss parameters, hence we determine the optimal input mean photon number, the optimal number of multiplexed units, and the optimal structure of the spatial multiplexer for which the single-photon probability of a spatially multiplexed single-photon source is maximal. We also analyze the effect of the probability distributions of the input photons on the optimal multiplexer structure and the output single-photon probability.

[1] E. Meyer-Scott, C. Silberhorn, A. Migdall, Rev. Sci. Instrum. **91**, 041101 (2020).

[2] P. Adam, M. Mechler, Appl. Sci. **14**, 11249 (2024).

[3] F. Bodog, M. Mechler, M. Koniorczyk, P. Adam, Phys. Rev. A **102** 013513 (2020).

[4] P. Adam, F. Bodog, M. Mechler, Opt. Express **30** 6999 (2022).

[5] P. Adam, F. Bodog, M. Koniorczyk, M. Mechler, Phys. Rev. A **105** 063721 (2022).

[6] P. Adam, M. Mechler, Opt. Express **31**, 30194 (2023).

[7] P. Adam; M. Mechler, Opt. Express **32**, 17173 (2024)

[8] M. Mechler, P. Adam, *Spatially multiplexed single-photon sources based on binary-tree multiplexers with optimized structure*, arXiv:2407.17370 (2024).

The Cumulant Expansion Approach: the Good, the Bad and the Ugly

J. Kerber[1], L. Ostermann[2] and H. Ritsch[3]

Institut für Theoretische Physik, Universität Innsbruck
Technikerstraße 21a, A-6020 Innsbruck, Austria

The configuration space, i.e. the Hilbert space, of compound quantum systems grows exponentially with the number of its subsystems: its dimensionality is given by the product of the dimensions of its constituents. Therefore a full quantum treatment, in general, is hardly possible analytically and can be carried out numerically for fairly small systems only. Yet, in order to obtain interesting physics, an approximation might very well suffice. One of these approximations is given by the cumulant expansion, where expectation values of products of operators are replaced by products of expectation values of said operators, neglecting higher-order correlations. The lowest order of these approximations is widely known as the mean field approximation and used routinely throughout quantum physics. Despite its ubiquitous presence, a general criterion for its applicability remains to be found. In this paper, we discuss two problems in quantum electrodynamics and quantum information, namely the collective radiative dissipation of a dipole-dipole interacting chain of atoms and the factorization of a bi-prime by annealing in an adiabatic quantum computer. On the one hand, we find smooth behaviour, where the approximation becomes increasingly better with higher orders, while, on the other hand, we are puzzled by completely uncontrolled solutions.

[1]johannes.kerber@uibk.ac.at
[2]laurin.ostermann@uibk.ac.at
[3]helmut.ritsch@uibk.ac.at

High-fidelity quantum control via the Autler-Townes effect

M. Delvecchio[1], T. Kirova[2], E. Arimondo[3], D. Ciampini[3], S.Wimberger[1]

[1]*Dipartimento di Matematica, Fisica e Informatica, Universitá di Parma, Italy*
[2]*Institute of Atomic Physics and Spectroscopy, FST, University of Latvia, Latvia*
[3]*Dipartimento di Fisica, Università di Pisa, Italy*

Quantum control is based on applying unitary transformations to various quantum systems in order to drive the population evolution into a target state. In a multilevel system with intrinsic interactions between the atomic/molecular levels (specifically spin-orbit interaction), the laser excitation may play a different indirect role. Namely, in the presence of strong electromagnetic fields, the energy levels in atoms/molecules experience shifts in their positions due to the so called Autler-Townes effect [1, 2].

Thus, the control of the spin-orbit interaction can be realized by using resonant or nonresonant laser fields with various parameters as an external control mechanism [3, 4].

By extending the scheme presented in [4] we explored the Autler-Townes control of spin-orbit coupling in an original four-level system aiming at large transfer efficiency to a final triplet state [5]. Our findings confirm the interesting features of probe-coupling excitation laser scheme, assisted by the intermediate spin-orbit coupling. The quantum control is based on the energy separation between the singlet and triplet states, modified by the Autler-Townes effect. The detuning and intensity of the control laser are proven to be key parameters of the control protocol.

This work is further developed into a theoretical description of an all-optical spin switch, where under the right system parameters the population can be transferred back and forth between the singlet and triplet states.

T. K. and S.W. acknowledge funding by Q-DYNAMO “Quantum Dynamic Control of Atomic, Molecular and Optical Process” (EU HORIZON-MSCA-2022-SE-01, Project No. 101131418). S.W. received support from the Italian National Quantum Science and Technology Institute (NQSTI).

References

[1] S. H. Autler and C.H. Townes, Phys. Rev. **100**, 703 (1955).

[2] E. H. Ahmed, et al. Advances in Atomic, Molecular, and Optical Physics, **61 (9)**, 467 (2012).

[3] T. Kirova and F.C. Spano, Phys. Rev. A **71**, 063816 (2005).

[4] E. H. Ahmed, S. Ingram, T. Kirova, O. Salihoglu, J. Huennekens, J. Qi, Y. Guan, and A. M.Lyyra, Phys. Rev. Lett. **107**, 163601 (2011).

[5] M. Delvecchio, T. Kirova, E. Arimondo, D. Ciampini, and S. Wimberger, Phys. Rev. A **106**, 052802 (2022).

From Lasers for Quantum Technologies to Optical Clocks

J. Koch

TOPTICA Photonics AG,
Lochhamer Schlag 19,
82166 Graefelfing, Germany

Lasers are one of the most important enabling technologies for applied and fundamental quantum technologies. They enable applications like quantum networks, quantum computers, quantum sensing, and quantum metrology. Over the last years, TOPTICA has developed laser systems that feature the high-end specifications required by research laboratories while meeting industry standards like ease-of-use, remote control and 19" rack footprint. In addition, TOPTICA provides solutions and customized developments for quantum industry and quantum academia. Our quantum technology solutions comprise tunable diode lasers including amplification and frequency conversion, low phase-noise lasers, frequency-stabilization to high-finesse ultra-stable optical cavities, optical frequency combs, electronics modules for laser phase and frequency stabilization, and light processing units. They are used, qualified, or partially developed within Quantum Flagship projects such as "Aqtion", "iqClock", "PASQuanS", "QIA", "Millenion", "PASQuanS2" or within German quantum technology projects.

We will describe our solutions – realized for quantum computing with neutral atoms, quantum computing with ions, quantum networks, and optical clocks –,discuss the results in the context of the applications mentioned, and present details and characterization of our ultra-stable clock laser systems for quantum computing and optical clocks "CLS". Rack-mounted and transport-stable without mechanical extra locking, it achieves relative frequency instabilities well below 2×10^{-15} from 0.1 s to 100 s at visible wavelengths.

Our currently most complex complete quantum technology solution builds on our experience obtained within the opticlock project (www.opticlock.de/en, [1]). We present our commercial optical frequency standard (OFS) research demonstrator that consists of two 19" rack compartments (RC). The RCs contain all subsystems to remotely operate the OFS that provides fiber output at 871 nm, i.e. half of the optical frequency of the $^{2}S_{1/2}$(F=0) – $^{2}D_{3/2}$(F=2) electric quadrupole ("E2") transition (436 nm) of a single trapped and laser cooled $^{171}Yb^{+}$ ion.
The RCs include:

- Frequency-stabilized lasers and optical subsystems to ionize, cool, repump, and detect Yb+ ions
- A clock laser, stabilized via a high finesse optical cavity to Hz level linewidths and used to drive the clock transition at 436 nm
- The ion trap physics package incl. vacuum system and optical addressing/imaging system
- Electronics modules to drive all systems
- Computer to remotely operate the system

Preliminary characterization of the OFS via interleaved operation promises relative frequency instabilities of $< 6 \times 10^{-15}/\mathrm{sqrt}(t)$, where t is the averaging time, and indicates averaging down to below 4×10^{-17} at 30,000 s.

References

[1] J. Stuhler et al., Measurement: Sensors, **18**, 100264 (2021). doi.org/10.1016/j.measen.2021.100264 .

Two-Photon Cooling of Calcium Atoms

S. Koch, W. Adamczyk, C. Politi, D. Kienzler, J. Home

Institute for Quantum Electronics, ETH Zurich, Otto-Stern-Weg 1, 8093 Zurich, Switzerland and Quantum Center, ETH Zurich, 8093 Zurich, Switzerland

Alkaline-earth(-like) atoms are typically cooled in a sequence of two magneto-optical traps (MOTs) [1]. A MOT operating on the broad $^1S_0 \rightarrow {}^1P_1$ line allows for effective capturing of atoms from a hot atomic beam. In a second stage, atoms are transferred to a MOT operating on the spin forbidden $^1S_0 \rightarrow {}^3P_1$ line, enabling microkelvin temperatures. In calcium however, this transition is only 400 Hz wide, requiring quenching to achieve sufficiently large scattering rates [2, 3]. In this work, we offer an alternative approach, in which we replace the narrow second stage MOT by a two-photon cooling scheme, effectively dressing the broad first stage MOT with a narrower linewidth transition [4, 5, 6, 7].
We characterized this cooling scheme in our calcium MOT [4]. A single infrared laser couples the upper state of the $^1S_0 \rightarrow {}^1P_1$ MOT to the $4s5s^1S_0$ state. The linewidth of the $^1P_1 \rightarrow 4s5s^1S_0$ transition is 4 MHz, corresponding to a Doppler temperature of about 100 µK. The temperature of the atomic sample can be tuned by varying the detuning from the intermediate state. In our setup, we are able to cool nearly 100% of the first stage atoms to 260 µK, well below the Doppler limit of the first stage MOT of 0.8 mK. Finally, we study the atom loss rate and find that the two-photon cooling scheme introduces no additional loss channels on top of the ones already present in the first stage MOT.
The proposed two-photon cooling scheme is straightforward to implement, achieves nearly 100% atom retention and allows tuning the effective linewidth of the dressed MOT. Due the relatively small mismatch of linewdiths between one- and two-photon MOT, the experiment can be run at a fixed magnetic field gradient. We are currently working on combining this cooling scheme with the loading of calcium atoms into optical tweezers.

[1] H. Katori, T. Ido, Y. Isoya, and M. Kuwata-Gonokami, Phys. Rev. Lett. 82, 1116 (1999).

[2] T. Binnewies, G. Wilpers, U. Sterr, F. Riehle, J. Helm- cke, T. E. Mehlstaubler, E. M. Rasel, and W. Ertmer, Phys. Rev. Lett. 87, 123002 (2001).

[3] E. A. Curtis, C. W. Oates, and L. Hollberg, Physical Review A 64, 031403 (2001).

[4] W. Adamczyk, S. Koch, C. Politi, H. F. Passagem, C. Fischer, P. Filippov, F. Berterottière, D. Kienzler, J. Home, `https://arxiv.org/abs/2411.16402` (2024)

[5] W. C. Magno, R. L. Cavasso Filho, and F. C. Cruz, Phys. Rev. A 67, 043407 (2003).

[6] N. Malossi, S. Damkjær, P. L. Hansen, L. B. Jacobsen, L. Kindt, S. Sauge, J. W. Thomsen, F. C. Cruz, M. Allegrini, and E. Arimondo, Phys. Rev. A 72, 051403 (2005).

[7] T. E. Mehlstaubler, K. Moldenhauer, M. Riedmann, N. Rehbein, J. Friebe, E. M. Rasel, and W. Ertmer, Phys. Rev. A 77, 021402 (2008).

Cascaded Frequency Conversion of NV-Center Fluorescence to the Telecom C-Band With Low Noise Spectral Density

F. von Chamier, J. Hanel, C. Müller, W. Li, R. A. Kögler, and O. Benson

Humboldt-Universität zu Berlin, Institut für Physik, Newtonstraße 15, 12489, Berlin, Germany

Different optical states and quantum devices often operate in disparate frequency modes. Frequency conversion plays then a crucial role in the interconnection of quantum network nodes [1]. In order to take advantage of current low-loss transmission lines, the conversion into the telecommunication C-band is of high interest. Using a two-step conversion integrated device, we successfully converted 637.2 nm light from NV centers in diamond with low internal (external) noise spectral density of 2.4 ± 0.8 (16 ± 5) cps/GHz [2]. The cascaded process bypass excess of noise introduced by spontaneous parametric down-conversion from the strong pump field.

Our highly integrated device consists of a periodic poled lithium niobate waveguide with two poling sections. The cascaded conversion spectrum with the involved fields in both difference-frequency conversion steps is shown in figure 1. Difference frequency generation between the pump (2152.9 nm) and our signal (637.2 nm) occurs in two steps, where the first (DFG1) and the second (DFG2) steps are shown in the output spectrum. The pump second harmonic (SHG) is also excited in the used device. The inset shows a higher resolution measurement of the spectral region from 1480 nm to 1620 nm, obtained with the combination of a tunable bandpass filter and single-photon detectors, revealing an extra peak near DFG2. We attribute this feature to a phase-matched conversion of thermal photons in the waveguide system [3].

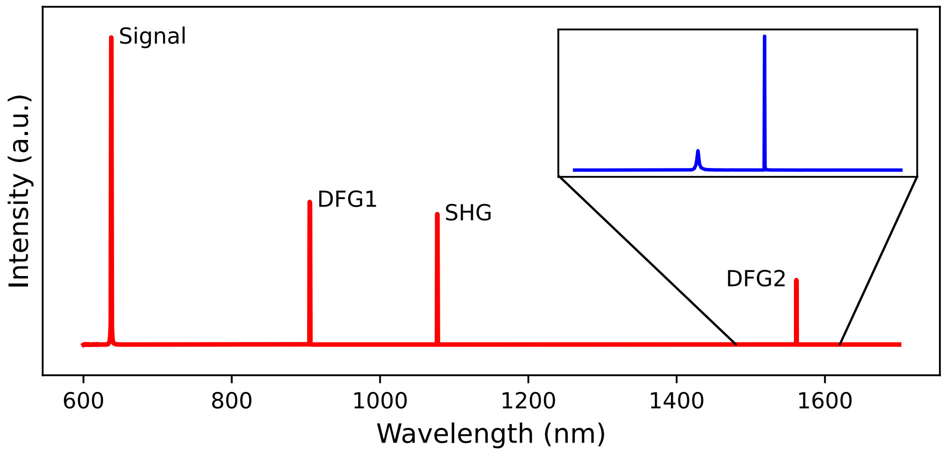


FIG. 1: Optical spectrum of the converter output. DFG1: first-step difference frequency generation. DFG2: second-step difference frequency generation. SHG: second-harmonic generation. The pump field is not shown due to experimental limitations in our detection systems.

Finally, we demonstrate the frequency conversion in a tunable region in the telecom C-band by thermally controlling the phase-matching conditions of each step. We reached target wavelengths between 1559.0 nm and 1564.9 nm with an external (internal) conversion efficiency of 3.0 ± 0.1 (20.5 ± 0.8) %.

References

[1] Kimble, H. Jeff. Nature 453.7198 (2008): 1023-1030.

[2] von Chamier, Fabrice, et al. arXiv preprint arXiv:2502.14557 (2025).

[3] C. Pedersen, et al. Opt. Express 22, 28027–28036 (2014).

Optical Quantum Process Tomography in Warm Atomic Vapors

M. Kopciuch[1], Y. Sun[2], A.D. Fard[2,3], S. Pustelny[2], A. Miranowicz[1]
[1] *Institute of Spintronics and Quantum Information, Faculty of Physics and Astronomy, Adam Mickiewicz University, 61-614 Poznań, Poland*
[2] *Marian Smoluchowski Institute of Physics, Jagiellonian University in Kraków, 30-348 Kraków, Poland*
[3] *Doctoral School of Exact and Natural Sciences, Jagiellonian University, Faculty of Physics, Astronomy and Applied Computer Sciences, Łojasiewicza 11, 30-348 Kraków, Poland*

Quantum Process Tomography (QPT) is one of the fundamental tools for the complete characterization of quantum system dynamics. It enables not only verification of the implementation of a desired quantum operation (e.g., a quantum gate) but also identification of relaxation mechanisms and reconstruction of the Hamiltonian governing the system. In this work, I present the implementation of QPT in a macroscopic cloud of rubidium atoms ($\sim 10^9$ atoms) at room temperature.

The reconstruction method employed is based on Quantum State Tomography (QST), realized via measurements of the linear Faraday effect — tracking the rotation of the polarization plane of a probe light beam propagating through the atomic medium [1–3]. During the presentation, I will demonstrate the full implementation of QPT in a qutrit system formed from the ground states of rubidium-87. I will show how the evolution of selected initial states allows for the estimation of processes occurring in atomic vapor, illustrated through basic quantum gates. Furthermore, I will present a method for reconstructing the generators of the observed dynamics — including time-independent dissipative generators, interaction Hamiltonians with residual fields, and time-dependent control Hamiltonians governing the evolution of the atomic cloud.

[1] M. Kopciuch, M. Smolis, A. Miranowicz, S. Pustelny, *Phys. Rev. A* **109**, 0324029 (2024).

[2] M. Piotrak, M. Kopciuch, A.D. Fard, M. Smolis, S. Pustelny, K. Korzekwa, *Quantum* **8**, 1459 (2024).

[3] M. Kopciuch, S. Pustelny, *Phys. Rev. A* **106**, 022406 (2022).

Non-Hermitian Dynamics of Atomic Systems: The Spectral Role of Quantum Jumps

M. Kopciuch[1], A.D. Fard[2,3], S. Pustelny[2], A. Miranowicz[1]

[1]*Institute of Spintronics and Quantum Information, Faculty of Physics and Astronomy, Adam Mickiewicz University, 61-614 Poznań, Poland*

[2]*Marian Smoluchowski Institute of Physics, Jagiellonian University in Kraków, 30-348 Kraków, Poland*

[3]*Doctoral School of Exact and Natural Sciences, Jagiellonian University, Faculty of Physics, Astronomy and Applied Computer Sciences, Lojasiewicza 11, 30-348 Kraków, Poland*

Non-Hermitian quantum physics has recently garnered significant interest due to its ability to describe energy dissipation in open quantum systems and to predict exotic phenomena such as exceptional points (EPs). In this context, non-Hermitian dynamics is often modeled using non-Hermitian Hamiltonians (NHHs). While these have been successfully applied in various platforms–particularly in photonic systems [1–3]–their use is now extending to a wider range of systems, including thermal atomic ensembles [4]. However, for some systems, an accurate description of the dynamics often requires a more complete treatment beyond NHHs [5–7].

We investigate this discrepancy using a model of an open atomic system with two hyperfine states ($F = 1$ and $F' = 0$), analyzed using the formalism of effective operators [8]. By comparing the eigenvalue spectra obtained from both an NHH and a Liouvillian superoperator, we analyze the emergence and properties of Hamiltonian and Liouvillian exceptional points, as well as diabolical points.

Our results show that, for atomic systems, relying solely on NHHs can be insufficient for accurately capturing the system's spectral features. While NHHs can provide correct predictions in specific scenarios, a full description generally requires the Liouvillian superoperator, which governs the Lindblad master equation and explicitly incorporates quantum jump terms. We demonstrate that the inclusion of quantum jumps via the Liouvillian formalism can fundamentally alter the spectral properties of the system. Specifically, we present examples where the existence, location in parameter space, or the order of spectral degeneracies differ significantly between the two approaches, underscoring situations where the NHH description breaks down.

Furthermore, by leveraging the hybrid-Liouvillian formalism [9], we illustrate how quantum jumps influence the spectral features predicted by the NHH, ultimately shaping the full spectrum as governed by the Liouvillian.

[1] Ş. K. Özdemir, S. Rotter, F. Nori, and L. Yang, *Nature Materials* **18**, 783 (2019).

[2] Y. Chen, F. Zhang, T. Qin, G. Zhao, J. Hou, X. Chen, L. Ge, and W. Wan, *Optica* **9**, 971 (2022).

[3] J. Doppler, A. A. Mailybaev, J. Böhm, U. Kuhl, A. Girschik, F. Libisch, T. J. Milburn, P. Rabl, N. Moiseyev, and S. Rotter, *Nature* **537**, 76 (2016).

[4] C. Liang, Y. Tang, A.-N. Xu, and Y.-C. Liu, *Phys. Rev. Lett.* **130**, 263601 (2023).

[5] W. Chen, M. Abbasi, Y. N. Joglekar, and K. W. Murch, *Phys. Rev. Lett.* **127**, 140504 (2021).

[6] S. Abo, P. Tulewicz, K. Bartkiewicz, K. Özdemir, and A. Miranowicz, *New J. Phys.* **26**, 123032 (2024).

[7] F. Minganti, A. Miranowicz, R. W. Chhajlany, and F. Nori, *Phys. Rev. A* **100**, 062131 (2019).

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

[9] F. Minganti, A. Miranowicz, R. W. Chhajlany, I. I. Arkhipov, and F. Nori, *Phys. Rev. A* **101**, 062112 (2020).

Experimental retrieval of photon statistics from click detection

S. Krishnaswamy[1], F. Schlue[2], L. Ares[1], V. Dyachuk[2], M. Stefszky[2], B. Brecht[2], C. Silberhorn[2], and J. Sperling[1]

[1] *Paderborn University, Institute for Photonic Quantum Systems (PhoQS), Theoretical Quantum Science, Warburger Straße 100, 33098 Paderborn, Germany*
[2] *Paderborn University, Institute for Photonic Quantum Systems (PhoQS), Integrated Quantum Optics, Warburger Straße 100, 33098 Paderborn, Germany*

Quantum light is one of the cornerstones in quantum technologies, making measurement of light all the more crucial. Photon statistics derived from photon-number-resolving detectors are often used to investigate the quantum nature of a light source. However, because of wider accessibility, we employ click detectors instead of photo-electric detectors. These detectors register a click irrespective of the number of incoming photons and no click otherwise. Therefore, click detectors yield a statistical distribution with properties different from common detection models [2].

Here, we utilize click-counting theory for the reconstruction of photon statistics, employing an analytic pseudo-inversion method [3] followed by loss deconvolution techniques [4]. Moreover, the theoretical model is verified with the help of a known light source, such as coherent light whose statistical properties for both photon-number-resolving and click detectors are well established. A reconfigurable time-bin multiplexing, click-counting detector is experimentally implemented for both $N = 4$ and $N = 8$ detection bins. We gauge the success of the reconstruction by applying the Mandel and binomial parameters, and a well-rounded comparison between the distinct statistical distributions is displayed. For coherent states, which lie at the classical-nonclassical boundary, both parameters are highly sensitive measures, probing the kind of statistics and the reconstruction performance. See Fig. 1 for a few results of our study [1].

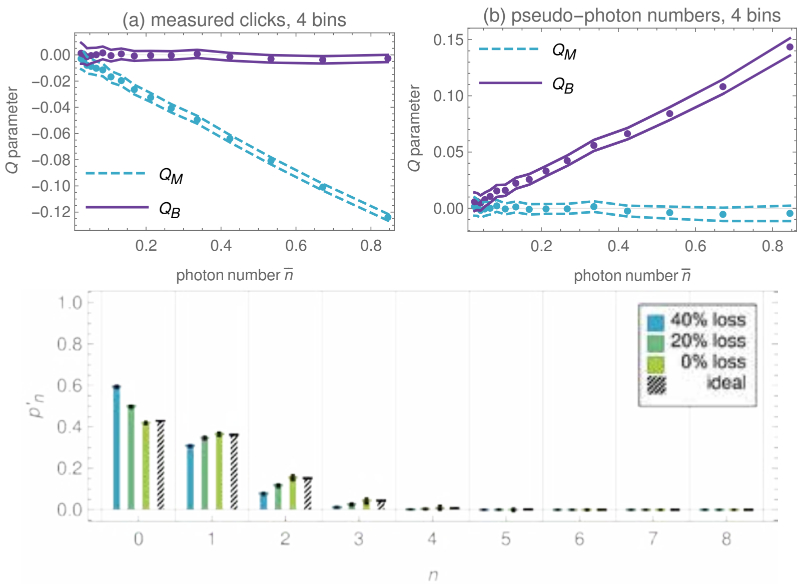


Figure 1: Plots (a) and (b). Mandel Q_M parameter and binomial Q_B parameter is used for verifying Poisson and binomial statistics, for $N = 4$ (bins). Bottom figure. The loss deconvolution (both full and half) of the retrieved pseudo-photon-number distribution with $N = 8$ bins.

References

[1] S. Krishnaswamy et al., Phys. Rev. A 110, 023717 (2024).

[2] J. Sperling, W. Vogel, and G. S. Agarwal, Phys. Rev. A **85**, 023820 (2012).

[3] O. P. Kovalenko, J. Sperling, W. Vogel, and A. A. Semenov, Phys. Rev. A **97**, 023845 (2018).

[4] A. A. Semenov, A. V. Turchin, and H. V. Gomonay, Phys. Rev. A **78**, 055803, (2008).

PI-45

Parity-time symmetry of the refractive index and its control in multilevel atomic system

V. Kudriašov[1], **H. R. Hamedi**[1], **G. Juzeliūnas**[1], **W.-T. Liao**[2]

[1] *Institute of Theoretical Physics and Astronomy, Vilnius University, Vilnius, Lithuania*
[2] *Department of Physics, National Central University, Taoyuan City, Taiwan*

The concept of parity-time (PT) symmetry has been explored across various fields of physics, including optics, atomic physics, acoustics, plasmonics, electrical circuits, and more. In particular, optics and photonics serve as an optimal platform for investigating PT-related phenomena [1-4], owing to the mathematical correspondence between the Schrödinger equation and the Maxwell equations in the paraxial approximation. Recent advancements in optical materials with diverse functionalities have driven significant progress in PT-symmetric optical theory, validated by series of relevant experiments [1]. Among the PT-symmetric systems, coherent atomic media exhibit unique properties, distinguishing them from other suitable optical structures [2-4]. In this study, we explore a novel approach using a four-level double-lambda (DL) atomic system (Fig. 1) for generating PT-symmetric spatially distributed refractive index profiles [5]. It is based on four-wave mixing, diverging from the previous methods relying on electromagnetically induced transparency (EIT), thus extending the PT-symmetry applications to atomic systems where EIT does not naturally arise. Position-dependent atomic coherences are generated and manipulated via the applied control fields and one-photon detuning (Fig. 1), leading to the establishment of PT-symmetries in the spatial distributions of the medium's refractive index. The PT-symmetry here can be achieved for the specific symmetry types of the control field and detuning functions, provided the phase-matching conditions are satisfied [5]. Pattern symmetries retain the stability throughout field propagation, whereas phase mismatch induces deviations, ultimately disrupting PT-symmetric profiles. The design of PT-symmetric spatially-distributed refractive index patterns enables the creation of corresponding optical potentials in DL atomic media, allowing for precise control and manipulation over light propagation, and can be used in a range of novel optical applications [5]. Furthermore, this study enhances the broader understanding of PT-symmetric systems, expanding their potential use across various physical and engineering disciplines.

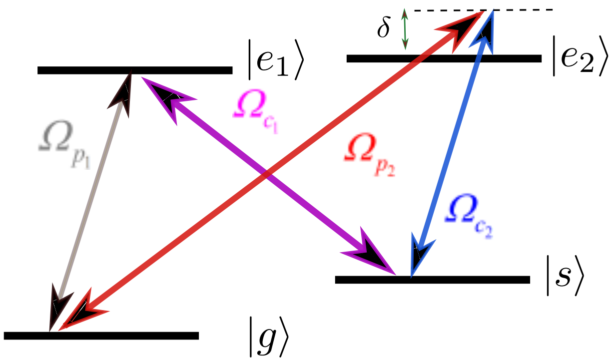


FIG. 1: Schematic representation of the double lambda atom-light coupling configuration. The medium is illuminated by two pairs of probe and control fields with some detuning.

References

[1] Y. Lv, B. Yin, M. Gao, S. Liu, H. Li, M. Wang, S. Wu, Results Phys. **51**, 106637 (2023).

[2] C. Hang, G. Huang, V. Konotop, Phys. Rev. Lett. **110**, 083604 (2013).

[3] J. Sheng, M.-A. Miri, D. N. Christodoulides, M. Xiao, Phys. Rev. A **88**, 041803(R) (2013).

[4] H.-J. Li, J. Dou, G. Huang, Opt. Express **21**, 32053 (2013).

[5] V. Kudriašov, W.-T. Liao, G. Juzeliūnas, H. R. Hamedi, Opt. Las. Tech. **175**, 110733 (2024).

Polarization Properties of Cavity Scattering by a Cold Ensemble of Atoms

Á. Kurkó[1], **D. Nagy**[1], **A. Vukics**[1] **and P. Domokos**[1]

[1] *HUN-REN Wigner Research Centre for Physics, Budapest, Hungary*

We experimentally investigate the polarization properties of light scattered from a cooled and trapped cloud of ^{8}7Rb atoms coupled to a high-finesse Fabry-Pérot optical resonator, where the illumination is transverse to the cavity axis. In the low-saturation regime, we perform a polarization-resolved analysis of the photons scattered into the cavity to map the nontrivial behavior of the coupled atom-cavity system under direct atomic drive. We observe a polarization rotation phenomenon, where the scattered light exhibits a component different from that of the drive field due to Raman scattering. By applying a second-order perturbative description to this transversely pumped scattering process, we develop a model that successfully describes the experimentally observed results in terms of two possible scattering channels: coherent Rayleigh and incoherent induced Raman scattering. Furthermore, within this framework, we demonstrate that the atomic array can serve as a source of completely coherent radiation. As direct evidence, we observe interference effects, providing experimental confirmation of this phenomenon.

Quantum Correlations of the Biphoton Decay in Colloidal Quantum Dots

Raul Lahoz Sanz[1, 2], Jose María Gómez Cama[1, 3] , Bruno Juliá Diaz[1, 2], Martí Duocastella Solà[1, 4]

[1]*Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (UB), C. Martí i Franquès, 1, 08028 Barcelona, Spain.*
[2]*Departament de Física Quàntica i Astrofísica, Facultat de Física, Universitat de Barcelona (UB), C. Martí i Franquès, 1, 08028 Barcelona, Spain.*
[3]*Departament d'Enginyeria Electrònica i Biomèdica, Universitat de Barcelona (UB), C. Martí i Franquès, 1, 08028 Barcelona, Spain.*
[3]*Departament de Física Aplicada, Universitat de Barcelona (UB), C. Martí i Franquès, 1, 08028 Barcelona, Spain.*

Colloidal quantum dots (CQDs) have garnered significant attention for quantum information science due to their unique optical properties and capability to function as efficient sources of single photons. These sources are usually deexcited emitting one photon, but they can also emit two photons in the same decay process, called biphoton decay [1]. In the biphoton decay, the first photon that exits the CQD is called the biexciton, while the second is called the exciton [2]. The theoretical equation for the wavefunction of this emission was reported in [3]

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|H_{XX}H_X\rangle + e^{i\frac{\delta\tau}{\hbar}}\,|V_{XX}V_X\rangle\right),$$

where the fine structure splitting (FSS) of the biphoton decay, called here δ, influences the photon-pair correlations by introducing oscillatory behavior between the entangled states HH+VV and HH-VV with a period of T = δ/h. τ is the delay time between the arrival of the exciton (X) and the biexciton (XX).

Our project aims to explore experimentally the quantum correlations resulting from the biphoton decay process in CQDs, predominantly focusing on CdSe/ZnS core-shell structures. By studying the correlation between the pairs of photons in the biphoton decay, we aim to determine if these pairs are entangled. For that purpose, we rely on the second-order autocorrelation function [4]. To measure the second order autocorrelation function, we use a Hanbury Brown and Twiss (HBT) setup integrated within a microscopy system, where we send the light emitted from one single CQD excited with a pulsed laser. Our setup is sketched in Fig. 1.

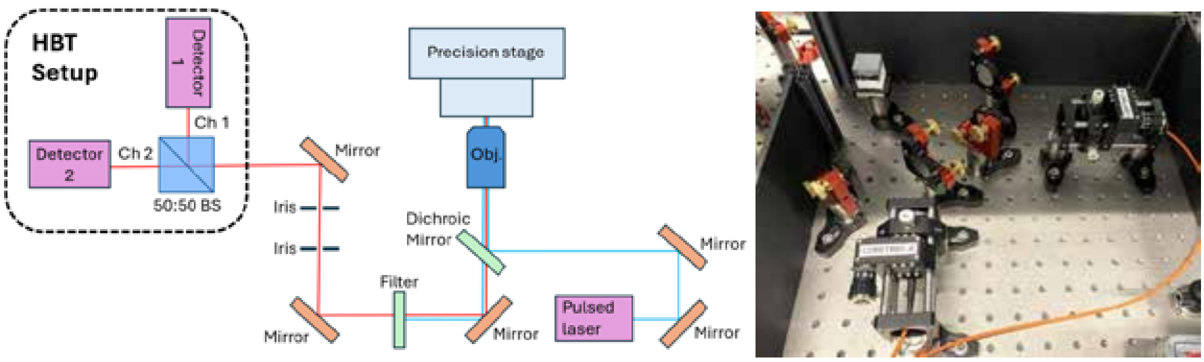


FIG. 1: Scheme of the setup for excite and collect light from one single CQD. Here is also shown the HBT setup which is used to perform the autocorrelation measurements. Some abbreviations are: BS. Beam Splitter. Obj. Objective. The image on the right shows our HBT setup

When the individual photons arrive to the HBT, they are equally split in two different paths leading to different detectors. Measuring the time delay between events registered in the different detectors, we can obtain the second-order autocorrelation graph. If we excite our CQD with pulsed light , the peak at zero delay time in this graph contains events in which an exciton was registered in one detector while the biexciton was registered in the other detector. Thus, with the second order autocorrelation function, we have a way of splitting the exciton and biexciton photon from the biphoton decay.

CEWQO29 - Experimentally Verifiable Criteria for Non-Gaussian Coherence

A. Lapras[1], B. E. Asenbeck[1], L. Lachman[1,2], A. Boyer[1], P. Giri[1], A. Urvoy[1], R. Filip[2], and J. Laurat[1]

[1] *Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, 4 Place Jussieu, 75005 Paris*
[2] *Department of Optics, Palacký University, 17. Listopadu 12, 771 46 Olomouc, Czech Republic*

Non-Gaussianity is a critical resource for advancing quantum technologies like fault-tolerant quantum computing, quantum networks, and high-precision metrology [1]. Unlike Gaussian states, non-Gaussian states cannot be efficiently simulated or characterized using classical methods. Characterizing non-Gaussian coherence, represented by the off-diagonal elements of a quantum state in the basis of interest, is crucial but challenging due to the absence of a canonical representation [2]. In recent years, our group has developed robust capabilities in non-Gaussian state engineering and networking applications, for example, the implementation of the first optical qubit encoding converter [3]. To build on these efforts, we propose a hierarchical framework for assessing non-Gaussian coherence in superpositions of Fock states, tailored to the specific requirements of various quantum applications [4].

This framework defines three thresholds: first, an absolute threshold, which establishes coherence criteria based on "free states" derived from Gaussian operations such as displacement and squeezing; then, a relative threshold, which refines this criterion by incorporating additional experimentally accessible parameters like photon number probabilities; and finally, a qubit-specific threshold, which modifies the framework to accommodate unbalanced superpositions in qubit systems. As illustrated in Fig.1, a Wigner-symmetric state undergoes a non-Gaussian unitary transformation $\hat{U}$, producing new coherences verified using the criteria developed in this study.

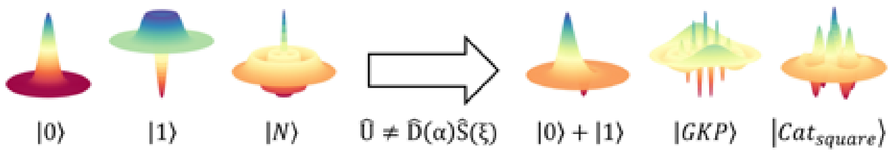


Fig. 1: Non-Gaussian coherence creation. A Wigner-symmetric state undergoes a non-Gaussian unitary transformation. The resulting state exhibits non-Gaussian coherences that can be verified via our criteria.

We tested this framework experimentally by generating heralded optical non-Gaussian states using optical parametric oscillators and single-photon detectors. States such as $|0\rangle - |1\rangle$ and $|0\rangle + |2\rangle$ were produced with single photon purities exceeding 90% and were characterized via homodyne tomography. Those states are able to meet some non-classical and non-Gaussian benchmarks, with limitations arising from residual Fock components and phase instabilities for the more advanced coherence thresholds. Our results show that relative thresholds provide a nuanced evaluation of non-Gaussian coherence [5].

This approach represents a significant advancement in the analysis of non-Gaussian coherence, effectively combining global properties with application-specific requirements. It demonstrates how experimental states can be assessed against customized thresholds. Future research could extend this methodology to complex quantum states, such as coherent-state superpositions and Gottesman-Kitaev-Preskill states, unlocking greater potential for quantum advantage in diverse applications.

References

[1] M. Walschaers. Non-gaussian quantum states and where to find them. *PRX Quantum*, 2, 2021.

[2] A. I. Lvovsky, P. Grangier, A. Ourjoumtsev, V. Parigi, M. Sasaki, and R. Tualle-Brouri. Production and applications of non-gaussian quantum states of light. 2020. URL `arXiv:2006.16985`.

[3] T. Darras, B. E. Asenbeck, A. Cavaillès, H. L. Jeannic, and J. Laurat. Non-gaussian quantum states and where to find them. *Nature Photonics*, 17, 2021.

[4] L. Lachman, B. E. Asenbeck, A. Boyer, P. Giri, A. Urvoy, J. Laurat, and R. Filip. Hierarchies of quantum non-gaussian coherences for bosonic systems: a theoretical study. URL `arXiv:2501.14033`.

[5] B. E. Asenbeck, L. Lachman, A. Boyer, P. Giri, A. Urvoy, R. Filip, and J. Laurat. Hierarchical verification of non-gaussian coherence in bosonic quantum states. URL `arXiv:2501.14032`.

Joint optimization of source and detectors for the discrete-variable quantum key distribution in the presence of strong classical signals

M. Lasota[1], J. M. Batalla[2], S. Sujecki[3,4], A. Ahmadian[1], P. Kolenderski[1]

[1] *Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziadzka 5, 87-100 Toruń, Poland*
[2] *Institute of Telecommunicaitons and Cybersecurity, Warsaw University of Technology, Nowowiejska 15/19, 00-665 Warsaw, Poland*
[3] *Faculty of Information and Communication Technology, Wrocław University of Science and Technology, Janiszewskiego 7/9, 50-372 Wrocław, Poland*
[4] *Department of Electronics, Military University of Technology, Kaliskiego 2, 00-908 Warsaw, Poland*

In the ideal scenario quantum key distribution (QKD) protocols offer unconditional security to its participants. However, in realistic conditions the security is strongly limited by numerous setup imperfections. Since installing dedicated fiber networks solely for the purpose of performing quantum communication is broadly considered to be unreasonable due to the extensive costs, one of the most important practical issues affecting QKD performance is related to the channel noise originating from strong classical data streams propagating alongside quantum signals. In particular, spontaneous Raman scattering phenomenon can easily dominate the other sources of noise and strongly limit the maximum QKD security distance, even when the power of classical signals is significantly reduced. This effect can be especially devastating for the discrete-variable (DV) QKD scenario, in which the quantum signals contain less than one photon on average [1].

Fortunately, the aforementioned problem can be considerably lessened by applying the temporal filtering method, as proposed in Ref. [2]. However, full potential of this method, that could be accessed with proper optimization of the QKD setup, has not been investigated yet. Such a study would be of great practical importance, especially since significant impact of setup optimization on the performance of QKD protocols has already been underlined in a couple of recent articles considering other communication scenarios [3,4].

In this work we fill the aforementioned gap by theoretically analyzing the DV QKD security in the presence of strong classical signals co- and/or counter-propagating with the quantum signal through the same fiber. We apply temporal filtering method to lower the Raman scattering noise and optimize it's performance by carefully choosing both the properties of photons produced by the sender's source and the duration of the detection windows established by the receiver. We consider both the prepare-and-measure and entanglement-based types of QKD setup configurations. For both of them we provide fundamental benchmarks on the power of classical signals, above which secure key generation would be impossible even for QKD parties utilizing ideal source and detectors of the quantum signals, with fully optimized characteristics.

Furthermore, as a realistic example we consider the coexistance of quantum and classical communication in the wired connections between the nodes of 6G network infrastructure. For the expected setup parameters in such a scenario we show that full optimization of the setup can extend the maximal security distance by 30 km (almost 50 km), comparing with the case of basic temporal filtering method, without any setup optimization (case of no temporal filtering, with detectors permanently opened). Considering the typical lengths of single links in metropolitan communication networks, such an extension is very significant. As a result, the considered idea of enhancing the security of 6G communication networks with QKD realized between the nodes, can be seen as a promising solution in realistic scenarios.

References

[1] B. Qi, W. Zhu, L. Qian and H.-K. Lo, New J. Phys. **12**, 103042 (2010).

[2] K. A. Patel *et al.*, Phys. Rev. X **2**, 041010 (2012).

[3] M. Lasota and P. Kolenderski, Sci. Rep. **10**, 20810 (2020).

[4] I. Maiti and M. Lasota, arXiv:2412.16007 (to be published in New. J. Phys.).

Exploring the Quantum Robustness of the Toric Code Using Neural Quantum States

E. Ledinauskas[1,2], **E. Anisimovas**[1]

[1] *Institute of Theoretical Physics and Astronomy, Vilnius University*
Saulėtekio al. 3, LT-10257, Vilnius, Lithuania
[2] *Baltic Institute of Advanced Technology, Pilies St. 16-8, LT-01403, Vilnius, Lithuania*

Neural Quantum States (NQS) have proven highly effective in studying the ground states of a diverse range of quantum many-body systems [1]. Recently, an innovative approach was introduced, extending the capabilities of NQS to compute not only ground states but also, in principle, an arbitrary number of excited states [2]. This method has been successfully demonstrated for various many-electron systems and opens intriguing possibilities, particularly for investigating systems with degenerate ground states.

The study of Hamiltonians with the toric code [3] as their ground state is of profound interest. These Hamiltonians exhibit a ground state degeneracy that depends on the topology of the system. The toric code stands out as one of the simplest paradigmatic examples, being particularly relevant to quantum error correction protocols [3]. Recent analytical approaches have explored the robustness of the toric code on a honeycomb lattice subjected to a uniform magnetic field by examining the quantum phase transition away from a topologically ordered state [4].

In this work, we enhance our previously developed NQS framework [5, 6] by incorporating the approach proposed in [2] to compute the energy gap between the degenerate ground states and the first excited state for varying magnetic field strengths. We find that accurately modeling this system poses significant challenges, requiring careful integration of prior knowledge about the toric code into the NQS training procedure.

Our main contributions are: (1) providing an insightful case study highlighting both the efficacy and practical challenges of the novel NQS excited-state method within strongly correlated topological systems characterized by highly degenerate ground states; (2) proposing practical strategies for incorporating prior knowledge about the toric code into NQS training; and (3) offering complementary insights into the robustness of the toric code on a honeycomb lattice under a uniform magnetic field.

[1] H. Lange, A. Van de Walle, A. Abedinnia, A. Bohrd. From architectures to applications: A review of neural quantum states. Quantum Science and Technology (2024).

[2] D. Pfau, S. Axelrod, H. Sutterud, I. von Glehn, J. S. Spencer. Accurate computation of quantum excited states with neural networks. Science, 385(6711) (2024).

[3] A.Y. Kitaev. Fault-tolerant quantum computation by anyons. Annals of physics, 303(1), 2-30 (2003).

[4] V. Kott, M. Mühlhauser J. A. Koziol, K. P. Schmidt. Quantum robustness of the toric code in a parallel field on the honeycomb and triangular lattice. SciPost Physics, 17(2), 053 (2024).

[5] E. Ledinauskas, E. Anisimovas. Scalable imaginary time evolution with neural network quantum states. SciPost Physics, 15(6), 229 (2023).

[6] E. Ledinauskas, E. Anisimovas. Universal performance gap of neural quantum states applied to the Hofstadter-Bose-Hubbard model. SciPost Physics, 18(1), 011. (2025).

Effects of the finite size of the illumination stage in correlation imaging setups

Giuseppe Lerario[1], Gianlorenzo Massaro[1,2], and Milena D'Angelo[1,2]

[1]Universita` degli studi di Bari, Dipartimento Interuniversitario di Fisica, Bari, I-70126, Italy

[2]Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Bari, I-70125, Bari, Italy

In the majority of correlation imaging setups, the effect played by the finite size of the illumination stage is generally overlooked when designing optical schemes. However, recent findings show that it can strongly influence the final outcome.

Correlation Plenoptic Imaging (CPI) is a recently developed imaging technique that overcomes the critical loss of resolution inherent in conventional Plenoptic Imaging (PI), enabling diffraction-limited resolution [1]. It does that by decoupling information about the light-field onto two high-resolution photodetectors. Very recently, the tomographic capabilities of CPI have been thoroughly analyzed. Specifically, it has been demonstrated that finite extension of the optical elements significantly impacts both the signal-to-noise ratio [2], [3] and the axial resolution, or, equivalently, axial sectioning capabilities [4].

In this context, by considering two case studies, free-space propagation and far-field illumination, the impact of the source is investigated. Notably, the measured quantity ends up depending on the source intensity profile and the illuminating source defines an effective numerical aperture in the correlation space, which can strongly affect the results of correlation imaging.

The study can be generalized also for better-known cases, such as Ghost Imaging. Here, it is well-known that the resolution is determined by the speckle size. Nevertheless, by considering out-of-focus configurations, it is discovered that the illumination stage greatly influences the achievable depth-of-field. Figure 1 shows how the point spread function (PSF) of ghost imaging changes with the defocusing parameter: the speckle dependence appears only for the plane in focus.

Maintaining control over the design of the illumination stage enables a more precise and optimized experimental design, ensuring that the full potential of the optical components is effectively exploited.

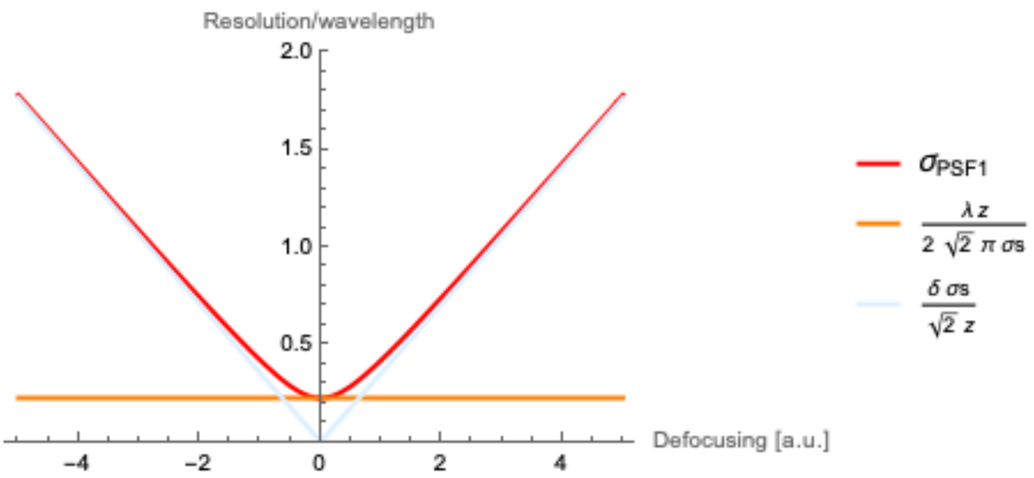


FIG. 1: Plot of the analytical expression describing the point spread function (PSF) of an out-of-focus Ghost Imaging setup. δ is the defocusing parameter, λ is the illumination wavelength, σ_s is the illuminating source size and z is the distance of the object from the source plane.

References

[1] F. V. Pepe *et al.*, "Diffraction-Limited Plenoptic Imaging with Correlated Light," *Phys Rev Lett*, vol. 119, no. 24, p. 243602, Dec. 2017, doi: 10.1103/PHYSREVLETT.119.243602/CPI_EXP_SM_PR_RESUB.PDF.

[2] G. Massaro, F. Di Lena, M. D'angelo, and F. V. Pepe, "Effect of Finite-Sized Optical Components and Pixels on Light-Field Imaging through Correlated Light," *Sensors*, vol. 22, no. 7, Apr. 2022, doi: 10.3390/s22072778.

[3] G. Massaro *et al.*, "Correlated-photon imaging at 10 volumetric images per second," *Scientific Reports 2023 13:1*, vol. 13, no. 1, pp. 1–8, Aug. 2023, doi: 10.1038/s41598-023-39416-8.

[4] G. Massaro, "Assessing the 3D resolution of refocused correlation plenoptic images using a general-purpose image quality estimator," *Eur Phys J Plus*, vol. 139, no. 8, Aug. 2024, doi: 10.1140/epjp/s13360-024-05493-5.

Polarization-entangled photon-pair source based on parametric optical frequency conversion in a photonic crystal fiber

Gustas Liaugminas[1], **Julijanas Želudevičius**[1], **Kęstutis Regelskis**[1]

1. Center for Physical Sciences and Technology, Savanoriu ave. 231, LT-02300 Vilnius, Lithuania

Polarization-entangled photon sources show great potential for the future use in quantum cryptography and sensitive data protection by means of Quantum key distribution (QKD) protocols [1]. Entangled photon pairs can be generated using SPDC process in periodically-poled crystals in a free-space setup [2]. However, to make entangled-pair source more robust and compatible with the currently existing telecom infrastructure a fiber-based alternatives appear more attractive and should be investigated. Degenerate four-wave mixing (FWM) in optical fibers is a known fiber-based method to produce polarization-entangled photon pairs. However, losses in optical fibers limit the practical operational distance when using such sources for QKD applications. One potential way to extend this distance is to match the idler photon wavelength with the low-loss telecom wavelength at ~1.5 µm while matching signal photon wavelength with the near-IR wavelengths used in quantum memories and quantum repeaters in the 637 – 800 nm range [3]. Photonic crystal fiber can be a good solution to this problem because its highly tunable physical parameters allow realization of different phase-matching scenarios. In this work we propose and investigate all-fiber architecture of entangled-photon source, which includes both ultrashort pulse generation in fiber [4] for pumping FWM process, and entangled-photon generation in photonic crystal fiber arranged in Sagnac loop configuration.

The schematic diagram of proposed setup is shown in Fig. 1 (a). The pump pulses are generated in a Mamyshev-type oscillator which is able to produce ~2 ps duration pulses with the center wavelength of 1030 nm [4]. These pulses are then stretched to ~ 160 ps duration, amplified in a fiber amplifier, pulse repetition rate reduced to 100 kHz and pulses amplified again up to maximum pulse energies of 400 nJ. Amplified pump pulses are then split into two arms using a polarizing beam-splitter and coupled into opposite ends of the photonic crystal fiber with mutually twisted polarization axis by 90°. Photonic crystal fiber is selected based on target signal/idler wavelengths and confirmed by numerical calculations of phase-matching conditions. Signal and idler waves are produced as a result of four-wave mixing inside photonic crystal fiber in both clock-wise and counter clock-wise directions. The use of the Sagnac loop ensures that signal and idler photons from both arms cannot be distinguished because of the same propagation path length and resulting signal/idler photon pair is in superposition of two polarization states.

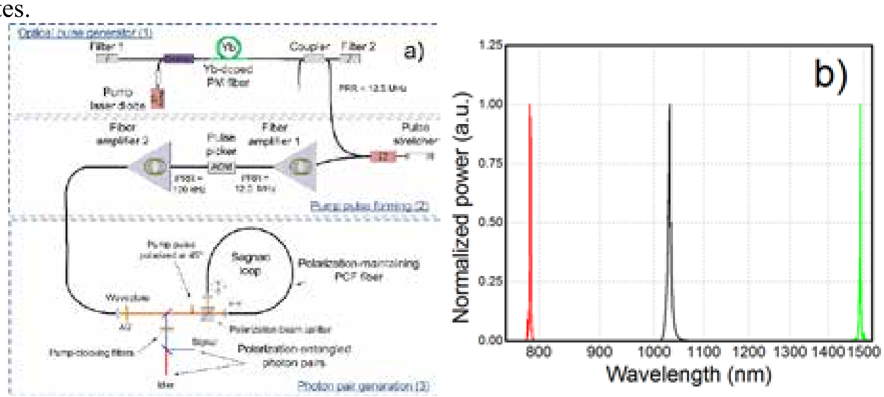


Fig. 1 a) Polarization entangled photon pair source setup (PRR – pulse repetition rate), b) Normalized experimental spectra of signal, pump and idler waves

Proposed setup was assembled and initial experiments of FWM generation in classical limit showed that target signal and idler wavelengths can be generated. By increasing the pump power of the fiber amplifier at the pump pulse energy threshold of ~400 nJ, the emergence of signal and idler waves was observed in the spectrum. The wavelengths of signal and idler waves matched well with the ones predicted from phase matching diagrams (λ_{signal}=785 nm, λ_{idler}=1490 nm). Additional experiments were performed by reducing the pump power to the level so that a single pair per pump pulse is generated. Further results characterizing the source and entanglement will be presented at the conference.

References

[1] M. Dusek, N. Lutkenhaus, and M. Hendrych, "Quantum Cryptography," Progress in Optics **49**, 381–454 (2006).
[2] Zachary H. Levine, Jingyun Fan, Jun Chen, and Alan L. Migdall, "Polarization-entangled photon pairs from a periodically poled crystalline waveguide," Opt. Express **19**, 6724-6740 (2011).
[3] J.L. Sanchez Toural, V. Marzoa, R. Bernardo-Gavito, J. L. Pau, and D. Granados, "Hands-on quantum sensing with NV-Centers in Diamonds," C. 9(**1**), 16 (2023).
[4] K. Regelskis, J. Želudevičius, K. Viskontas and G. Račiukaitis in, "Ytterbium-doped fiber ultrashort pulse generator based on self-phase modulation and alternating spectral filtering," Opt. Lett, **40**, 5255-5258 (2015).

Witnessing genuine continuous-variable contextuality and Bell non-locality

C.E. Lopetegui-González[1], P.E. Emierau[2], U. Chabaud[3], G. Masse[4], E. Oudot[4], U.I. Meyer[4], F. Grosshams [4], R. Booth[5,6], D. Markham[4], F. Centrone[7], M. Walschaers[1]

[1] *Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, 4 place Jussieu, F-75252 Paris, France*
[2] *Quandela, 7 Rue L'eonard de Vinci, 91300 Massy, France*
[3] *DIENS, École Normale Supérieure, PSL University, CNRS, INRIA, 45 rue d'Ulm, Paris, 75005, France*
[4] *Sorbonne Université, CNRS, LIP6, F-75005 Paris, France*
[5] *University of Edinburgh, United Kingdom*
[6] *University of Bristol, United Kingdom*
[7] *ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, Mediterranean Technology Park, Avinguda Carl Friedrich Gauss 3, 08860 Castelldefels, Barcelona, Spain*

Contextuality and Bell non-locality represent fundamental non-classical features of quantum systems that serve as resources for quantum computational and communicational advantages. Bell non-locality is a special case of contextuality. In particular, for multipartite scenarios, with only local measurement allowed, the contextual fraction – a quantifier of contextuality – is equivalent to a normalised Bell inequality violation.

Although the original EPR paradox was formulated in terms of continuous variables, most studies of these phenomena have focused on discrete-variable scenarios. Recently, a continuous-variable formalism of contextuality was introduced in [1] along with a method to quantify the amount of contextuality in a physical experiment. This method is a continous-variable generalisation of the contextual fraction as a solution of an infinite-dimensional linear program. A hierarchy of semi-definite programs converging to the contextual fraction is also provided in [1]. Yet, no explicit experiment that would witness a genuine continuous-variable violation of a Bell inequality was provided in [1].

Our work uses this method and provide explicit example to probe the genuine continuous-variable Bell inequality violation. With respect to previous strategies employed on continuous variable settings, here we do not need to hand pick a binary discretization of the data, but rather rely directly on the histograms obtained from homodyne detection, with a homogeneous binning. Using this strategy, we find out that, for some previously studied empirical models [2-4], the Bell inequality violations obtained, when normalized to unity, are exactly equivalent to the contextual fraction, meaning they are optimal for the homodyne settings and states that they consider. Notably, these examples include two-photon subtracted states, which are within the reach of state of the art quantum optics experiments.

References

[1] R.S. Barbosa, T. Douce, P.E. Emeriau, E. Kashefi, and S. Mansfield, Communications in Mathematical Physics **391**, 1047-1089 (2022).

[2] J. Wenger, M. Hafezi, and F. Grosshans, R. Tualle-Brouri, and P. Grangier, Physical Review A **67**, 1 (2003).

[3] R. García-Patrón, J. Fiurášek, and N. J. Cerf, J. Wenger, R. Tualle-Brouri, and P. Grangier, PRL **93**, 13 (2004).

[4] E. Oudot, G. Massé, X. Valcarce, and A. Acín, *arXiv:2402.01530* (2024).

THEORETICAL INVESTIGATION OF GUIDED MODE RESONANCE EFFECT IN OPTICAL GAIN CAVITIES

I. Lukošiūnas[1], **K. Staliūnas**[2]

[1] *Vilnius University, Laser Research Center, Sauletekio Ave. 10, Vilnius, Lithuania*
[2] *ICREA, Passeig Lluís Companys 23, 08010, Barcelona, Spain*
[3] *UPC, Dep. de Fisica, Rambla Sant Nebridi 22, 08222, Terrassa (Barcelona), Spain*

The guided mode resonance (GMR) is an effect introduced by R. Magnusson in thin modulated dielectric cavities, characterized by narrow-band reflection and transmission properties, high resonance quality factors, as well as its applications for spatial filtering in laser systems, polarization filters, and angular dispersion control [1]. Such devices are broadly studied, however, only as passive filters that exhibit no optical gain. Structures with optical gain can enhance the transmitted and reflected radiation via an introduced imaginary refractive index, where the imaginary part corresponds to the exponential amplification of the guided mode's amplitude. The concept of enhanced radiation via incorporating gain is illustrated in Fig. 1.

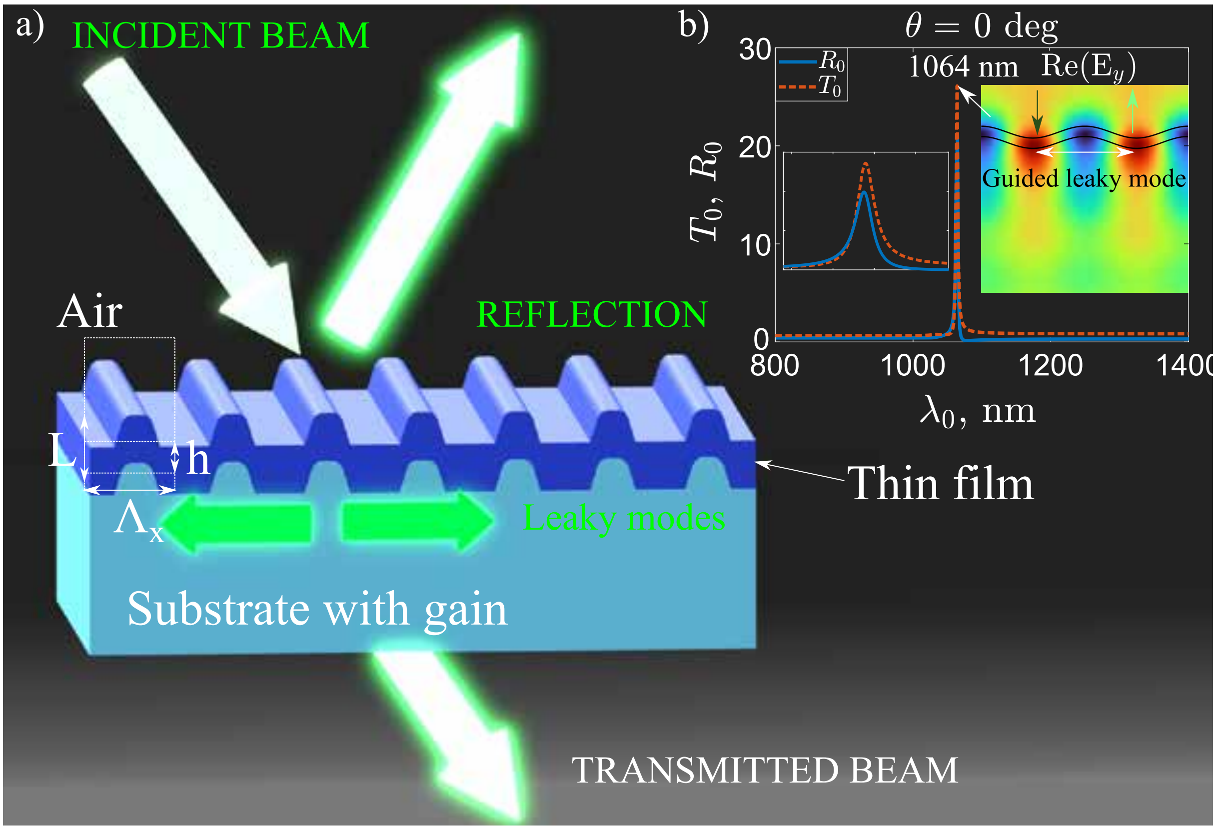


Fig. 1. The concept of an active meta-mirror: a) the incident beam coupled into the waveguiding mode of the thin film. b). Reflection/transmission dependence on the wavelength by crossing the resonance along with the field distribution at the peak of spectral response.

The gain material is introduced as a perovskite with an imaginary refractive index capable of exponentially amplifying diffraction efficiencies [2]. With proper optimization algorithms and numerical tools [3], the device geometry can be tuned to achieve high resonance quality factors and optimal coupling between incident radiation, excited guided modes, and the radiation itself, thus maximizing the reflection and transmission coefficient values. Such structures can be used as angle sensitive amplifiers, low-pass amplifiers in laser systems. In this work, we apply a genetic optimization algorithm with the 2D RCWA method to achieve device designs that exhibit enhanced gain via the GMR effect. We also expand on the analytical model, which we use to explain the behavior and characteristics of the achieved results quantitatively.

Magnetically generated spin-orbit coupling for ultracold atoms with slowly varying periodic driving

D. Burba[1], M. Mackoit-Sinkevičienė[1], V. Novičenko[1], E. Witkowska[2], and G. Juzeliūnas[1]

[1] *Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio 3, 10257 Vilnius, Lithuania*

[2] *Institute of Physics PAS, Aleja Lotników 32/46, 02-668 Warszawa, Poland*

Spin–orbit coupling (SOC), the interaction between a quantum particle's spin and its momentum, plays a crucial role in spintronics and quantum information processing. Over the past decade, SOC has also attracted significant attention in the context of ultracold atomic systems. In these systems, SOC can give rise to novel many-body phases and opens up promising applications in areas such as spintronics [1] and precision measurements [2,3].

In this work, we show how to bypass the micromotion emerging in the magnetically induced SOC by switching on and off properly the oscillating magnetic fields at the initial and final times (see Fig. 1) [4]. We analyze the exact dynamics of the system throughout the entire evolution and show that, under these conditions, the overall dynamics can remain immune to micromotion effects. Furthermore, the exact dynamics agrees well with the evolution of the system described by the slowly changing effective Floquet Hamiltonian which contains the SOC term. The best agreement is achieved when the phase of the periodic driving is tuned to a specific value, maximizing the effect of the SOC. In that case, the first-order effective Floquet Hamiltonian vanishes and the zeroth-order Floquet Hamiltonian remains accurate up to the second-order expansion in the inverse powers of the driving frequency. Our findings thus provide strong evidence that the magnetically induced SOC can be generated in a controllable way without involving micromotion [4].

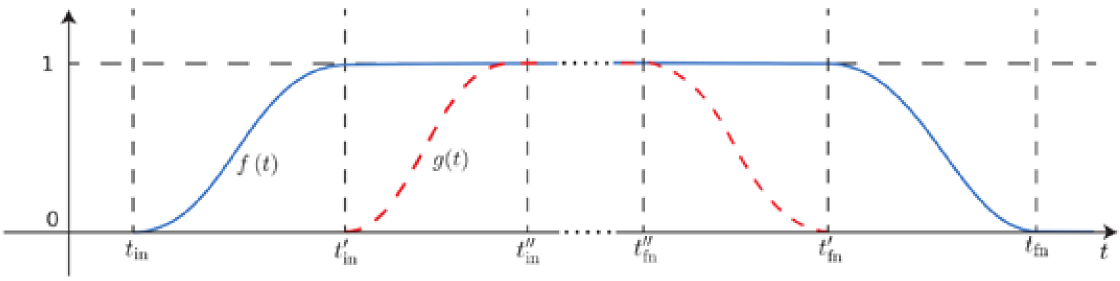


FIG. 1: Schematic representation of the switching on and off of the slowly varying amplitudes $f(t)$ and $g(t)$ of the gradient and Zeeman fields represented by blue solid and red dashed lines, respectively.

The reduction of the micromotion effect opens the path for the SOC implementation in systems where the Raman coupling is difficult to apply, for example, for light atoms like lithium for which the fine-structure splitting responsible for the SOC is very small. In that case the Raman transitions inducing the SOC should be very close to the excited-state resonance in order to resolve the fine structure, which might lead to significant losses. The magnetically generated SOC does not rely on the fine-structure splitting and thus provides a method for creating the SOC for a wide range of atoms including the light ones.

References

[1] C. S. Madasu, M. Hasan, K. D. Rathod, C. C. Kwong, and D. Wilkowski, *Phys. Rev. Res.* **4**, 033180 (2022).

[2] M. Mamaev, I. Kimchi, R. M. Nandkishore, and A. M. Rey, *Phys. Rev. Res.* **3**, 013178 (2021).

[3] T. Hernández Yanes, M. Płodzień, M. Mackoit Sinkevičienė, G. Žlabys, G. Juzeliūnas, and E. Witkowska, *Phys. Rev. Lett.* **129**, 090403 (2022).

[4] D. Burba, M. Mackoit-Sinkevičienė, V. Novičenko, E. Witkowska, G. Juzeliūnas, *Phys. Rev. A* **109**, 053319 (2024).

PII-8

Bounding deterministic Gaussian conversion protocols for conversion of non-Gaussian states

Oliver Hahn[1,2,*], **Patric Holmvall**[3,*], **Alex Maltesson**[1], **Cameron Calcluth**[1], **Giulia Ferrini**[1], **Alessandro Ferraro**[4]

[1] *Wallenberg Centre for Quantum Technology, Department of Microtechnology and Nanoscience, Chalmers University of Technology, Sweden, Göteborg SE-412 96, Sweden*
[2] *Department of Basic Science, The University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan*
[3] *Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden*
[4] *Quantum Technology Lab & Applied Quantum Mechanics Group, Dipartimento di Fisica "Aldo Pontremoli", Universit'a degli Studi di Milano, I-20133 Milano, Italia*
[*] These authors contributed equally to this work.

In this study, we aim to bound the maximum fidelity that can be achieved with simple single- and two-mode deterministic Gaussian conversion protocols for the transformation of possibly mixed non-Gaussian states to a pure non-Gaussian state. Gaussian protocols comprise a sub-universal set of operations that can be efficiently simulated on a classical computer when restricted to states with a non-negative Wigner function. However, they are typically assumed to be readily available in experimental settings because they are practically easy to implement. This makes them interesting to study, as understanding their limitations helps define the boundaries of what can be achieved with physically realizable operations. We have investigated the potential of using deterministic Gaussian protocols consisting only of Gaussian unitary operations and partial trace for the conversion of non-Gaussian states to pure non-Gaussian states. We consider two circuits: A single-mode protocol, which only consists of a Gaussian unitary, and a two-mode protocol, which includes a two-mode Gaussian unitary and a partial trace. For these circuits, we study bounds on the possible fidelity between the output state and the target state. We provide strong numerical evidence that the two-mode protocol, using two copies of the same input non-Gaussian state, does not increase the fidelity to the target state, as compared to the case of the single-mode protocol. We also discuss possible avenues for an analytical proof of such a result.

Local purity distillation and the geometric entanglement

Piotr Masajada[1], Alexander Streltsov[2]

[1] *Institute of Fundamental Technological Research Polish Academy Of Sciences, Pawinskiego 5B, Warszawa*
[2] *Institute of Fundamental Technological Research Polish Academy Of Sciences, Pawinskiego 5B, Warszawa*

Quantifying entanglement in a given quantum state remains a challenging problem. Over the years, several entanglement measures have been developed, each with its own advantages and limitations. Among them, geometric entanglement stands out as a particularly useful quantifier. However, computing its value is computationally demanding.

In this poster, we present a method for efficiently computing geometric entanglement for mixed bipartite and pure multipartite systems using semi-definite programming. Our approach opens new possibilities for practical applications, particularly in entanglement detection and estimation. We illustrate this by evaluating entanglement in a class of bound entangled states, as well as in output states of certain noisy quantum channels. Additionally, we analyze entanglement in spin chain systems.

Our method draws upon techniques from two fundamental quantum resource theories: the resource theory of entanglement [1] and thermodynamics [2]. These resource theories represent two pivotal quantum resource theories with significant relevance in quantum information science. Despite their importance, the intricate relationship between these two theories is still not fully understood. Here, we investigate the interplay between entanglement and thermodynamics, particularly in the context of local cooling processes. We introduce and develop the framework of Gibbs-preserving local operations and classical communication. Within this framework, we explore strategies enabling remote parties to effectively cool their local systems to the ground state. We focus on systems with fully degenerate local Hamiltonians, where local cooling aligns with the extraction of local purity. In this context, we establish a powerful link between the efficiency of local purity extraction and the degree of entanglement present in the system, a concept we define as *purity-entanglement complementarity.*

References

[1] Horodecki, P. Horodecki, M. Horodecki, and K. Horodecki, Quantum entanglement, Rev. Mod. Phys. 81, 865 (2009).

[2] G. S. L. Brandão, M. Horodecki, J. Oppenheim, J. M. Renes, and R. W. Spekkens, Resource Theory of Quantum States Out of Thermal Equilibrium, Phys. Rev. Lett. 111, 250404 (2013).

Optimal measurement induced squeezing for CV cluster states

M. Matulík[1], **R. Filip**[1],
P. Marek[1]

[1]*Department of Optics, Palacký University, Olomouc, Czech Republic*

In recent years, there has been rapid development in continuous variable quantum computing. Cluster states are commonly created in laboratories [1]. On the way to quantum supremacy, the Gaussian gates should be implemented as efficiently as possible because cluster states suffer from losses. We find the optimal method for squeezing in the simplest cluster state - teleportation scheme. The teleportation scheme in continuous variables can be adapted to teleport and squeeze the input state. This can be done by changing the measurement angles of the homodyne detectors. A new approach of squeezing has been introduced. The static beam splitters are replaced with variable ones. We compare these two methods using the fidelity and the Wigner function. We find that the newly introduced method is superior.

References

[1] M. Larsen,et al., Deterministic generation of a two-dimensional cluster state, Science 366, 369, (2019)

PII-11

A fiber testbed and a quantum repeater cell for quantum communication

J. Meiers[1], C. Haen[1], M. Bergerhoff[1], O. Elshehy[1], E. Arenskötter[1], S. Kucera[1,2], T. Bauer[1], C. Becher[1], J. Eschner[1]

[1] *Experimentalphysik, Universität des Saarlandes, Saarbrücken, Germany.*
[2] *Luxembourg Institute of Science and Technology (LIST), Belveaux, Luxembourg.*

The realization of a quantum internet [**1**] requires the implementation and benchmarking of quantum communication protocols over deployed fiber links, which pose challenges such as polarization drift, losses from splices, and environmental perturbations. Furthermore, quantum repeaters (QR) are essential, they overcome the exponential attenuation of direct transmission by dividing the communication link into smaller segments of asynchronously entangled quantum nodes. To scale quantum hardware from laboratory systems to real-world applications, miniaturization and modularity are equally important.
We report on the operation and active stabilization of a 14.4 km deployed urban fiber link across the town of Saarbrücken (Fig. 1(a)) for quantum communication. The polarization drift is stabilized to a process fidelity of $> 99\%$ for durations exceeding 60 s. Using an ion-resonant entangled photon pair source based on parametric down-conversion and a $^{40}Ca^{+}$ single-ion quantum memory, we demonstrate high-fidelity entanglement distribution over the link. Using heralded absorption of one photon of the entangled pair by the trapped ion, we demonstrate atom-to-photon quantum state teleportation across the link with an average fidelity of $\sim 84\%$[**2**].
In a laboratory setting, we demonstrate a QR cell based on asynchronous generation of atom-photon entanglement from two $^{40}Ca^{+}$ ions in the same Paul trap. Photon-photon entanglement is generated by a Mølmer–Sørensen gate and atomic state projection, achieving an average fidelity of $\sim 76\%$ [**3**].
In preparation for QR networks with device-independent security, we also demonstrate a device-independent quantum key distribution (DIQKD) protocol in the laboratory, paving the way for future implementation over the urban fiber link (Fig. 1(b)).
Finally, we present the development of a segmented ion trap with an integrated sub-mm cavity to increase the collection efficiency of emitted photons and enable compact, rack-mountable quantum communication hardware suitable for repeater-based architectures.

(a) (b)

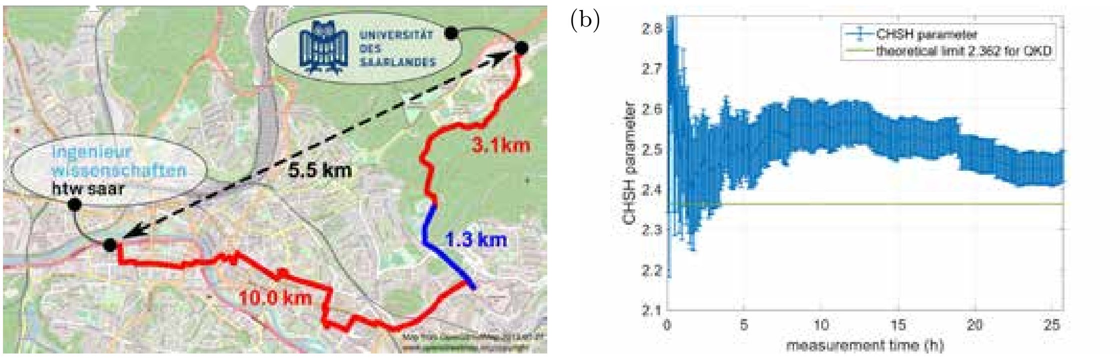


Figure 1: (a) Map of the fiber link across Saarbrücken. It comprises 1.3 km of aerial fiber (blue)
(b) DIQKD protocol: evolution of the CHSH parameter over time.

References

[1] H. Kimble, The quantum internet. Nature 453, 1023–1030 (2008).

[2] S. Kucera, et al. Demonstration of quantum network protocols over a 14-km urban fiber link. npj Quantum Inf 10, 88 (2024).

[3] M. Bergerhoff, et al. Quantum repeater node with free-space coupled trapped ions, Phys. Rev. A 110, 032603 (2024).

Photon Number States via Iterated Photon Addition in a Loop

Barna Mendei, **Mátyás Koniorczyk**

Eötvös Loránd University, Faculty of Natural Sciences, Pázmány Péter sétány 1/A, 1117 Budapest, Hungary
HUN-REN Wigner Research Centre for Physics, Konkoly-Thege Miklós út 29-33., 1121 Budapest, Hungary

B. Mendei[1], **M. Koniorczyk**[2]

[1] *Eötvös Loránd University, Faculty of Natural Sciences*
[2] *HUN-REN Wigner Research Centre for Physics*

The preparation of n-photon states, that is, the implementation of sources emitting a specific number of photons, is an important problem in many quantum optics and quantum information applications. In this work, we analyse the possibility of using an arrangement consisting solely of a periodic single-photon source [1], a beam splitter, mirrors, and a realistic photon detector. The setup consists of a loop in which we employ Hong–Ou–Mandel interference to achieve iterative photon addition. Its purpose is to generate an arbitrary n-photon Fock state probabilistically, conditioned by measurement results. These states exhibit strong non-classical behaviour. The literature typically proposes more complex schemes for their generation. In this work, we demonstrate that our arrangement [2] composed only of passive linear optical elements, can generate up to four-photon states with reasonable fidelity and probability even with imperfect detectors. Our work also contributes to the better understanding of photonic interferometric loops which are important in photonic quantum computing.

[1] P. Adam, M. Mechler, I. Santa, and M. Koniorczyk, Phys. Rev. A **90**, 053834 (2014).

[2] B. Mendei, M. Koniorczyk, G. Homa and P. Adam, Photonics **11**, 1075 (2024).

Dynamics of strongly coupled harmonic oscillators in Gaussian noisy channels

T. Mihaescu, A. Isar

Horia Hulubei National Institute for Research and Development in Physics and Nuclear Engineering, str. Reactorului 30, Magurele-Bucharest, Romania

We investigate the Markovian evolution of Gaussian entanglement and steering in a system consisting of two strongly coupled harmonic oscillators immersed in a structured environment. Specically, we analyze the contribution of the interaction between modes when the magnitude of the intermode coupling strength is comparable to the local frequencies of the modes, and the rotating wave approximation does not apply. Previously, the intermode strong coupling was considered in the case of a common thermal bath [1], and presently we extend this investigation to a generalized Gaussian channel, when the environment is modeled by a collection of squeezed bosonic modes. We also provide an extended comparison of the evolution of entanglement and steering in weak and strong coupling regimes [2].

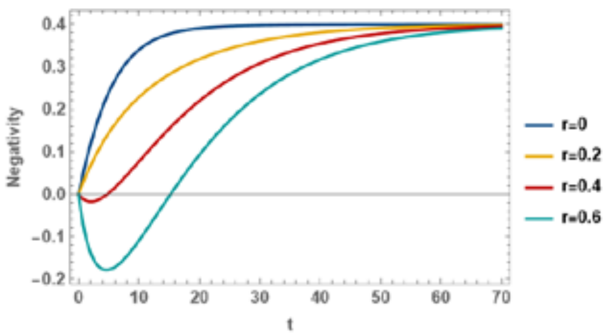


FIG. 1: Time dependent evolution of logarithmic negativity for simmetric coupling $q_1 = q_2 = 0.4$.

References

[1] J. F. Sousa, C. H. S. Vieira, J. F. G. Santos, I. G. da Paz, Coherence behaviour of strongly coupled bosonic modes, Phys. Rev. A **106**, 032401 (2022).

[2] T. Mihaescu, A. Isar, Dynamics of strongly coupled harmonic oscillators in Gaussian noisy channels, (to be published).

PII-14

Phase Sensitivity for a parametric amplifier-enhanced unbalanced Mach-Zehnder interferometer

Karunesh K. Mishra[1], **Ilinca Butu**[1], **Stefan Ataman**[1]

[1] *Extreme Light Infrastructure - Nuclear Physics (ELI-NP), 'Horia Hulubei' National R&D Institute for Physics and Nuclear Engineering (IFIN-HH), 30 Reactorului Street, 077125 Măgurele, jud. Ilfov, Romania*

Interferometry is a ubiquitous technique for achieving high phase sensitivity. Nowadays, quantum interferometry is increasingly used in multiple scientific and technological domains [1]. It has been shown that conventional Mach-Zehnder interferometer (MZI) can see its phase sensitivity enhanced by the addition of parametric amplifiers (PA) [2, 3, 4]. This is especially interesting when low photon fluxes are required, for example, in the case of imaging biological samples [5].

Previous studies have shown that, even for a conventional MZI, the optimal configuration is not necessarily the balanced (50/50) case [6, 7]. Moreover, in the lossy scenario, the balanced case becomes the exception, not the rule [8].

In this work, we address the optimum phase sensitivity of a PA-enhanced interferometer, fed by a coherent input state. Thus, in the upper (lower) arm of an MZI we add a PA, characterized by the gain denoted $g_1 = \sinh r_1$ ($g_2 = \sinh r_2$). Contrary to previous studies [4], we address the unbalanced scenario, where both beam splitters (BS) have an adjustable transmission coefficient (denoted τ_1 and τ_2, respectively). Multiple detection schemes are considered, both with and without access to an external phase reference [9]. We asses their performance by computing the corresponding quantum Fisher information (QFI) denoted $\mathcal{F}$ for each scenario. This tool allows us to compute the quantum Cramér-Rao bound (QCRB) and we are thus able to compare the performance of each considered detection scheme.

The optimal configurations are identified for each scenario. Our results reveal that, for a difference intensity detection scheme, the optimum transmission coefficient τ_1^{opt} of the first beam splitter depends on the PA gains. Indeed, from QFI maximization one finds

$$\tau_1^{opt} = \frac{|\alpha|^2 e^{2r_1} + \frac{\sinh^2 2r_1}{2e^{2r_1}} - \frac{\sinh^2 2r_2}{2e^{2r_2}}}{|\alpha|^2 \left(e^{2r_1} + e^{2r_2}\right)}. \tag{1}$$

leading to an optimum two-parameter QFI

$$\mathcal{F} = \frac{2\left(2|\alpha|^2 + \frac{\sinh^2 2r_1}{e^{4r_1}} + \frac{\sinh^2 2r_2}{e^{4r_2}}\right)}{\left(e^{-2r_1} + e^{-2r_2}\right)^2}. \tag{2}$$

The balanced case ($\tau_1 = 0.5$) reported [4] in the literature is only optimal when the gains are equal, as seen from equation (1). In contrast, for detection schemes having access to an external phase reference, one finds the optimum QFI

$$\mathcal{F} = 4|\alpha|^2 e^{4r_2} + 2\sinh^2 2r_2 \tag{3}$$

and this optimum is usually found in the degenerate case (*i. e.* $\tau_1 = 1$). The force-balanced case is also evaluated, and it is shown that its performance is suboptimal. We also show that a homodyne detection scheme is able to approach the QFI (3) induced QCRB, $\Delta\varphi_{QCRB} = 1/\sqrt{\mathcal{F}}$.

References

[1] M. Paris, Int. J. of Quantum Info. **07**, supp01, 125 (2009).

[2] C. Vitelli et al., Phys. Rev. Lett. **105**, 113602 (2010).

[3] Z. Y. Ou, Phys. Rev. A **85**, 023815 (2012).

[4] X. Zuo et al., Phys. Rev. Lett. **124**, 173602 (2020).

[5] M. A. Taylor and W. P. Bowen, Physics Reports **615**, 1 (2016).

[6] S. Ataman and K. Mishra, Phys. Rev. A **105**, 012604 (2022).

[7] K. Mishra and S. Ataman, Phys. Rev. A **106**, 023716 (2022).

[8] S. Ataman and K. Mishra, Phys. Rev. A **109**, 062605 (2024).

[9] M. Jarzyna, R. and Demkowicz-Dobrzański, Phys. Rev. A **85**, 011801(R) (2012).

An All-Gaussian Quantum Neural Network

H. Nagayoshi[1], **W. Asavanant**[1,2], **I. D. Smith**[3], **H. P. Nautrup**[3], **R. Ide**[1], **A. Furusawa**[1,2,4]

[1] *Department of Applied Physics, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*
[2] *OptQC Corp., 1-16-15 Minami-Ikebukuro, Toshima, Tokyo, Japan*
[3] *University of Innsbruck, Institute for Theoretical Physics, Technikerstr. 21A, Innsbruck, Austria*
[3] *Optical Quantum Computing Research Team, RIKEN Center for Quantum Computing, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

Continuous-variable quantum computing (CV-QC) is a paradigm of quantum information processing that takes advantage of the continuous nature of bosonic systems for analog computation.Recently, a scalable implementation of CV-QC with time-domain multiplexing on optical platforms has been proposed and experimentally demonstrated [1,2], which is expected to achieve an ultrafast computation of a THz clock frequency at room temperature in the future. Although research paves the way for fault-tolerant CV-QC with optical components both theoretically and experimentally, current technologies have yet to realize universal quantum computing . In the upcoming era of noisy intermediate-scale devices, it is crucial to find experimentally feasible use cases for practical computation.

In the qubit regime, variational quantum circuits (VQCs) [3] are vigorously investigated as a promising application of quantum devices. Although previous papers [4] have partially extended this framework to CV-QC, these proposals raise numerous challenges for experimental implementation, such as high-demanding photon interactions and a lack of analysis on sampling costs, to name a few. To overcome these obstacles, we present an experimentally feasible ansatz for CV quantum machine learning. As illustrated in Fig. 1(a), the VQC employed here consists only of Gaussian gates, enabling a straightforward implementation by a measurement-based quantum computation scheme using cluster states [2]. To realize nonlinear data processing only with Gaussian operations, we examined data-reuploading ansatz and adaptive feedforwarded operations. As shown in Fig.1(b), the circuit can be successfully trained for multiple tasks such as curve fitting and binary classification. We further analyze the sampling cost and discuss potential techniques to increase its performance such as parameter-shift gradient estimation [6].

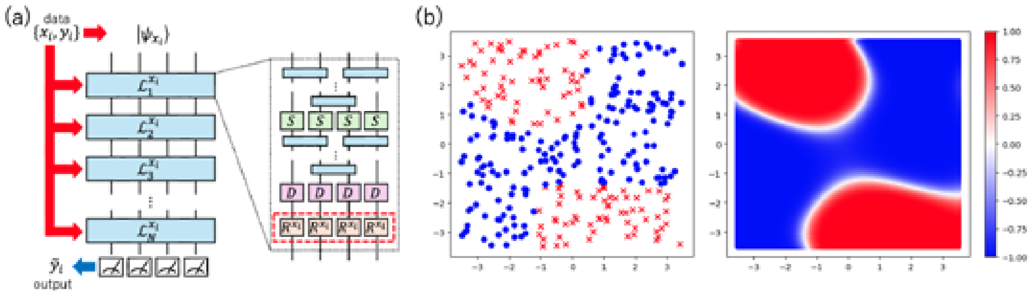


FIG. 1: (a) An all-Gaussian variational quantum ansatz. Each layer consists of fully-connective Gaussian transformation, followed by Gaussian gates parametrized by either the input data or partial measurement results. (b) Simulation result for biclassification task on the 2D plane.

References

[1] W. Asavanant *et al.*, Science **366**, 373 (2019).

[2] M. V. Larsen, J. S. Neergaard-Nielsen, and U. L. Andersen, Phys. Rev. A **102**, 042608 (2020).

[3] M. Cerezo *et al.*, Nat Rev Phys **3**, 625 (2021).

[4] M. Schuld, V. Bergholm, C. Gogolin, J. Izaac, and N. Killoran, Phys. Rev. A **99**, 032331 (2019).

[5] N. Killoran, T. R. Bromley, J. M. Arrazola, M. Schuld, N. Quesada, and S. Lloyd, Phys. Rev. Research **1**, 033063 (2019).

Low-vibration cryostat towards high-performance quantum memories in a rare-earth ion-doped crystal

H. Naim[1], M. Khilfa[1], C. Pitiot[1], F. Zumbo[1], A. Tempel[2], S. Bosio[1], S. Tanzilli[1] and J. Etesse[1]

[1] *Institut de Physique de Nice, Université Côte d'Azur, 06000 Nice, France*
[2] *LOMA, Université de Bordeaux, 33405 Talence Cedex*

Quantum memories have been an active research in quantum optics, for they are essential for quantum information processing. One of the most prominent platforms is rare-earth ion-doped crystals, used with the atomic frequency comb (AFC) protocol [1]. To reach the highest coherence times, these crystals need to be cooled down at cryogenic temperatures (∼3 K), but current state-of-the-art commercially available closed-cycle systems suffer from inevitable vibrations, caused either by mechanically moving pieces or gaz turbulences. Such vibrations induce detrimental piezospectroscopic shifts, that hinder the preparation of fine population structures, as required for the AFC protocol [2].

We present here the development of a cryostat whose architecture is designed for minimizing vibration propagation between the cold head and the sample. The body of the cryostat, the radiation shieldings as well as sample pieces were all machined in order to achieve high precision adjustment in the space-constrained environment of the cryostat, where the final currently operating version is shown in Figure 1. Our realization aims at being simultaneously low vibration, compact as well as modular, while reaching a base temperature below 4 K. The key vibration isolation feature is a mechanical decoupling between the cold head part and the experimental chamber via elastic vacuum connection and via the use of copper braids for thermal connection.

We estimate the performances of the cryostat by two means. The first means consists in burning a narrow hole in the inhomogeneously broadened absorption line of a praseodymium-doped yttrium orthosilicate (Pr:YSO) crystal. By monitoring in real time the hole width and position, we assess the effect of vibration on spectral features. With our setup we reach hole widths of 20 kHz, monitored with a free-induction-decay (FID) protocol, for durations of the order of 400 ms, as shown in Figure 2.

The second characterization means consists in implementing the AFC protocol in the Pr:YSO crystal for storage of coherent states of light, for storage durations ranging between 2 and 40 μs. By fitting the exponential decay of the efficiency η as a function fo the storage time τ, we reach a coherence time T_2 of 88 μs, already at the level of state-of-the-art values.

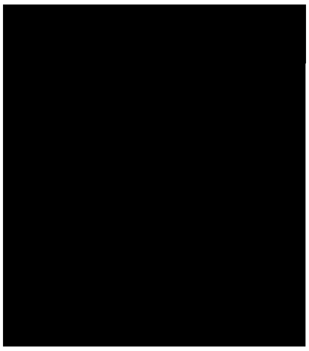


Figure 1: The cryostat: chamber (left) and cold head housing (right)

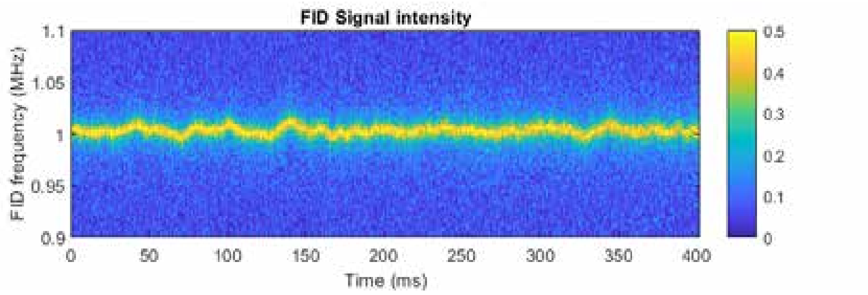


Figure 2: Spectral hole position tracking using FID protocol

References

[1] M. Afzelius, C. Simon, H. de Riedmatten, and N. Gisin, "Multimode quantum memory based on atomic frequency combs", Physical Review A **79**, 052329 (2009)

[2] A. Louchet-Chauvet, R. Ahlefeldt and T. Chanelière "Piezospectroscopic measurement of high-frequency vibrations in a pulse-tube cryostat", Rev. Sci. Instrum. **90**, 034901 (2019).

Multimode Squeezed States in Telecom and the Mode-Selective Production of Non-Gaussian States Induced by Waveguides

P. Namdar

Laboratoire Kastler Brossel, Sorbonne University, CNRS, ENS-PSL University, Collège de France, 4, Place Jussieu, 75005 Paris, France

P. Namdar[1], D. Fainsin[1], R. L. Rincón Celis[1], V. Roman-Rodriguez[2], G. L. Zanin[3], N. Treps[1], and V. Parigi[1]

[1]*Laboratoire Kastler Brossel, Sorbonne University, CNRS, ENS-PSL, Collège de France, France*
[2]*ICFO – Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, Castelldefels, 08860 Barcelona, Spain*
[3]*Instituto de Física, Universidade Federal de Goiás, 74001-970, Goiânia, Brazil*

Extensive spectro-temporal control is essential for advancing quantum optical applications. While successfully realizing a source of multimode Gaussian states, non-Gaussian features are indispensable in many quantum protocols, especially to reach quantum computational advantage [1]. Therefore, we not only present an improved multimode squeezed state source in the telecom regime, but also a scheme to extend the setup to generating non-Gaussian states, currently being implemented.

We have accomplished a continuous-variable multimode squeezed state source operating in the telecom regime. In its initial configuration, the source demonstrated squeezing across 21 frequency modes [2]. To further enhance the degree of squeezing, we upgraded key components of the setup, including an increase on the spectral width of the local oscillator (LO) beam used for homodyne detection and the implementation of a self-optimizing wavefront shaping scheme. These improvements aim to boost coherence within the different components of the projective measurements, which could already provide higher squeezing values. Moreover, this strategy provides valuable feedback on the wavefront-shaping characteristics of the involved waveguides. In parallel, we have advanced the setup towards pulse-by-pulse measurements, which enable the direct implementation of fast quantum protocols and advanced information processing.

As a next step, we aim to incorporate non-Gaussian processes into our system by realizing mode-selective single-photon addition and subtraction on the generated telecom quantum light. These operations build on theoretical schemes developed within our group [3-5] and were further extended in this work to be compatible with our existing source, but can easily be adapted to any other spectral regime.

While our initial modeling focused on metallic waveguides—and by approximation, also conventional diffused waveguides—we have now extended it to thin-film lithium niobate waveguides, enabling us to leverage their currently intensively studied sub-wavelength confining nonlinear behavior.

In summary, we present a multimode squeezed state source in the telecom regime with enhanced resolution and squeezing performance. We further outline its extension toward a source of non-Gaussian states, with the capability to mode-selectively generate tailored quantum states. Our theoretical framework provides a complete description of the required processes, and we are currently implementing these methods in our experimental setup. Therefore, this work expands the platform for advanced quantum information processing in photonic networks.

References

[1] A. Mari and J. Eisert, "Positive Wigner functions render classical simulation of quantum computation efficient," *Phys. Rev. Lett.* **109**, 230503 (2012).

[2] V. Roman-Rodriguez *et al.*, "Multimode Squeezed State for Reconfigurable Quantum Networks at Telecommunication Wavelengths," *Phys. Rev. Res.* **6**, 043113 (2024).

[3] V. Averchenko, V. Thiel, and N. Treps, "Nonlinear photon subtraction from a multimode quantum field," *Phys. Rev. A* **89**, 063808 (2014).

[4] V. Averchenko, C. Jacquard, V. Thiel, C. Fabre, and N. Treps, "Multimode theory of single-photon subtraction," *New J. Phys.* **18**, 083042 (2016).

[5] G. Roeland, S. Kaali, V. Roman Rodriguez, N. Treps, and V. Parigi, "Mode-selective single-photon addition to a multimode quantum field," *New J. Phys.* **24**, 043031 (2022).

Toward Neutral Atom Array Quantum Processors in Singapore

Zilong Chen[1], Thanh Nguyen[1], Mujahid Aliyu[1], Vasu Dev[2], Tong-Yan Xia[1], Vincent Mancois[2], David Wilkowski[12]

[1] *Centre for Quantum Technologies, National University of Singapore, Singapore 117543.*
[2] *Centre for Disruptive Photonic Technologies, SPMS, The Photonics Institute, Nanyang Technological University, Singapore 637371, Singapore.*

The development of 200 qubits or more quantum processors is divided into subtasks running in parallel to tackle the various technical and conceptual challenges. On the technical side, we are developing a compact 2D MOT, a science chamber for the 3D MOT with an ultrahigh vacuum environment, and a 2D tweezer array of neutral atoms. The 2D MOT segment improves the atom flux and segregates the vacuum for the 3D MOT thanks to a differential tube. The atoms are cooled down to the microKelvin range in the 3D MOT and loaded in the tweezer array. On the conceptual side, we are evaluating key atomic transitions for the realization of quantum computing operations. We are also working on developing static tweezer arrays using spatial light modulators to trap the atoms. Subsequently, we will be developing mobile tweezers for the rearrangement of the atoms during the later stages of the project.

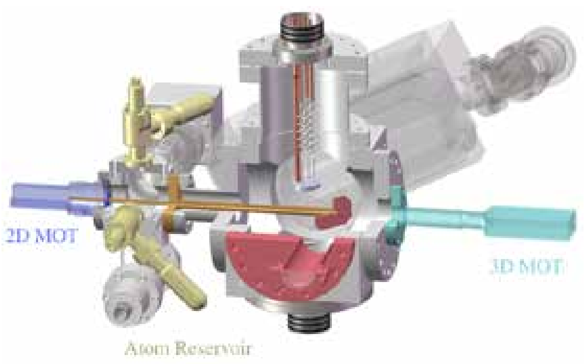


Figure 1: Science Chamber

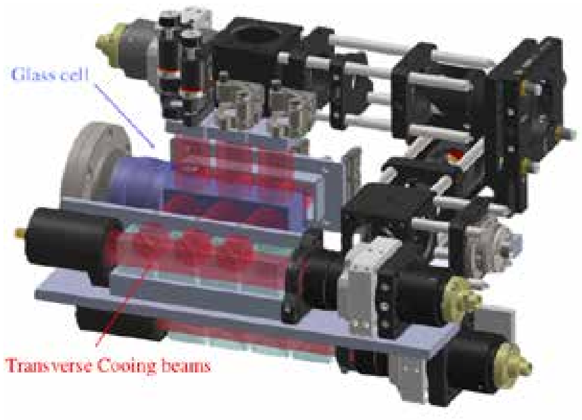


Figure 2: 2D MOT

Ac-Stark lattice modulation method to achieve long-lived collective Rydberg excitations in atomic gas

B. Niewelt[1,2], S. Kurzyna[1,2], M. Mazelanik[1], W. Wasilewski[1,2], M. Parniak[1,2]

[1] *Centre for Quantum Optical Technologies, Centre of New Technologies, University of Warsaw, Banacha 2c, 02-097 Warsaw, Poland*
[2] *Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*

Collective Rydberg excitations have become an area of increasing interest across various important domains of physics. These excitations show great promise for applications in fields such as quantum information processing, quantum simulators, and ultra-sensitive electrometry[**1**]. However, their potential is constrained in practical situations by their short thermal dephasing time, which, at typical experimental temperatures of around $\sim 100\,\mu\text{K}$, is typically limited to no more than a microsecond. While some advanced techniques exist to extend the atomic coherence lifetime, they have only been applied to ground-state quantum memories. Applying these methods to Rydberg excitations would require substantial modifications to make them compatible.

We propose a novel approach based on Ac-Stark phase modulation of a quantum memory ensemble, which has the potential to freeze atomic coherence and completely suppress thermal decoherence effects. This protocol was implemented by interfering two off-resonant laser beams with the atomic medium, demonstrating that it is possible to achieve a ten-fold increase in lifetime[**2**]. To validate our findings, we simulated the evolution of atomic coherence in phase space, accounting for factors such as the finite duration of the modulation pulses, imperfect alignment of the experimental setup, and atomic motion across various velocity classes.

Our experimental results showed an improvement in lifetime by more than a factor of 10, approaching the natural lifetime of the Rydberg state limited by spontaneous and radiative dephasing. The proposed protocol enables measurements of Rydberg interactions over extended timescales, which is often essential for applications in electrometry or for utilizing long-lived collective qubits in quantum simulations and computational interfaces with light.

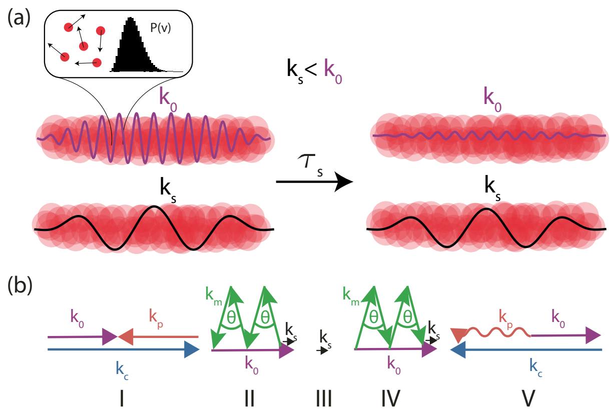


Figure 1: (a) Blurring of the spinwaves with different wavevectors due to thermal motion of the ensemble. Spinwaves with larger wavevector are more affected by motional dephasing. (b) Geometrical representation of the stages of the extended lifetime protocol.

References

[1] S. Borówka, U. Pylypenko, M. Mazelanik, and M. Parniak. “Continuous wide-band microwave-to-optical converter based on room-temperature Rydberg atoms”. Nature Photonics **18**,32–38 (2024).

[2] S. Kurzyna, B.Niewelt, M. Mazelanik, W. Wasilewski, and M. Parniak. ”Long-lived collective Rydberg excitations in atomic gas achieved via ac-Stark lattice modulation”. Quantum **8**, 1431 (2024).

Suitable interaction picture for the high-frequency expansion of periodic Hamiltonians belonging to $\mathfrak{su}(3)$ Lie algebra

V. Novičenko[1], **E. Anisimovas**[1]

[1] *Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio ave. 3, LT-10257 Vilnius, Lithuania*

Periodic Hamiltonians with additional slow time dependence are promising examples of realizing non-Abelian (noncommuting) geometric vector potential in ultra-cold atoms or any other quantum system. To be more precise, in the regime when the frequency is high enough (higher than any other characteristics of the quantum system), one can perform inverse frequency expansion and obtain an effective Hamiltonian which, due to additional slow time, realizes the geometric vector potential [1]. Yet, such a vector potential appears as the second-order term, meaning that the zero and the first-order terms have a higher impact on the overall dynamics. One can move the relevant part of the Hamiltonian (the part which creates the geometric vector potential) to the zero-order term by considering high amplitudes (the amplitudes proportional to the frequency) of the external periodic force [2]. While such an approach is convenient in a experimental realization of the geometric vector potential [3], it goes with the price that we need to work in the interaction picture. The unitary transformation for the interaction picture is known only for the Hamiltonians belonging to $\mathfrak{su}(2)$ Lie algebra [2]. We aim to extend this limitation to $\mathfrak{su}(3)$ Lie algebra.

References

[1] V. Novičenko, E. Anisimovas, G. Juzeliūnas: Phys. Rev. A **95**, 023615 (2017).

[2] V. Novičenko, G. Juzeliūnas: Phys. Rev. A **100**, 012127 (2019).

[3] L. W. Cooke, A. Tashchilina, M. Protter, J. Lindon, T. Ooi, F. Marsiglio, J. Maciejko, L. LeBlanc: Phys. Rev. Research **6**, 013057 (2024).

Work Extraction from Squeezed Thermal State with Unknown Phase

E. Postavová, Š. Bräuer, T. Opatrný

Department of Optics, Faculty of Science, Palacky University, 17. listopadu 50, 77146 Olomouc, Czech Republic

The variety of types of heat machines is large and can even extend into the field of quantum optics. States can be divided into passive and non-passive states depending on whether work can be extracted from them using unitary processes. The non-passivity of a state allows extraction of work through unitary operations [1]. Recent research has shown the possibility of transforming initially passive states, such as thermal states, into nonpassive states through nonlinear interferometer interactions with vacuum field [2]. The goal now is to establish whether it is possible to utilize such states and extract work from them.

The potential work extractable from a squeezed thermal state with an unknown phase, also known as ergotropy [3], has been investigated. Two different approaches are explored: reordering of Fock states and phase estimation.

1. In the first approach, it is demonstrated how highly nonlinear unitary transformations can reorder the probability distribution of the squeezed state, enabling energy extraction. This reordering results in a passive state as the outcome. While such unitary operations do not exist in practice, there is potential for their realization using transmons [4].
2. In the second approach, a setup is proposed where the main goal is to estimate the phase and perform following feedforward. This idea is inspired by Maxwell's demon, which performs a measurement before extracting work from a system. A fraction of the state is split for phase estimation, which is performed by applying rotation and antisqueezing, followed by photon number detection. This optimal estimate then allows for optimal anti-squeezing of the remaining part of the state.

In both cases, it is demonstrated that work can be extracted from the input state, which could have potential applications in quantum thermodynamics.

References

[1] W. Pusz, S. L. Woronowicz, Commun. math. Phys. **58**, (1978).

[2] N. Meher, T. Opatrný, and G. Kurizki, Quantum Sci. Technol. **9**, (2024).

[3] A. E. Allahverdyan, R. Balian, and T. M. Nieuwenhuizen, Europhys. Lett. **67**, (2004).

[4] M. Kudra, T. Abad, M. Kervinen, A. M. Eriksson, F. Quijandría, P. Delsing, and S. Gasparinetti, Phys. Rev. Applied **20**, 054046 (2023).

Exploring Synchronization of Multimode Squeezed States of Light in a Continuous Variable Quantum Network

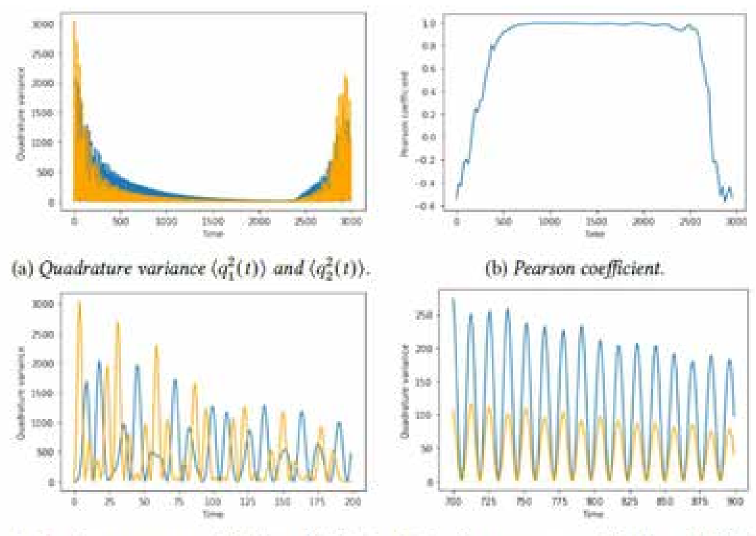
Radivoje Prizia [1], Francesca Sansavini [2], Johan Henaff [1], Nicolas Treps [1], Roberta Zambrini [3], and Valentina Parigi [1]

[1]Laboratoire Kastler Brossel, Sorbonne Université, ENS-Université PSL, CNRS, Collège de France, 4 place Jussieu, Paris F-75252, France

[2]Department of Physics and Oregon Center for Optical, Molecular, and Quantum Science, University of Oregon, Eugene, Oregon 97403, USA

[3]Institute for Cross-Disciplinary Physics and Complex Systems (IFISC) UIB-CSIC, Campus Universitat Illes Balears, Palma de Mallorca, Spain

Synchronizations are common phenomena in nature, observed in several classical dynamical systems in biology, physics, and chemistry. Notable examples are the synchronous flashing of male fireflies and the synchronous movement of a swarm of birds. This phenomenon is also being studied in the quantum domain in terms of its link to quantum features such as entanglement correlations. In this work, we focus on two bosonic oscillators dissipating into an environment (bath) of bosonic oscillators. Mutual synchronization occurs when the two oscillators, despite having different frequencies, begin to oscillate in unison at a common frequency. Our aim is to realise an experimental optical platform to simulate the Hamiltonian of the system and to observe the emergence of synchronization by looking at the evolution of the quadrature variances of the two oscillators [1]. The simulation of the dynamics of a network of quantum oscillators at a given time can be obtained via squeezing operations followed by linear optics, via measurement basis change. Moreover, we assess the effect of the number of oscillators and of the squeezing level on synchronization, as they are our main experimental constraints.



(a) Quadrature variance $\langle q_1^2(t)\rangle$ and $\langle q_2^2(t)\rangle$. (b) Pearson coefficient.

(c) Quadrature variance $\langle q_1^2(t)\rangle$ and $\langle q_2^2(t)\rangle$ during the first part of the dynamics, the two oscillators are not synchronized. (d) Quadrature variance $\langle q_1^2(t)\rangle$ and $\langle q_2^2(t)\rangle$ at a later stage of the dynamics, the two oscillators are synchronized.

Figure: Numerical simulation of quantum synchronisation. The decrease of synchronization observed in (b) is due to finite-size effects. [1]

References

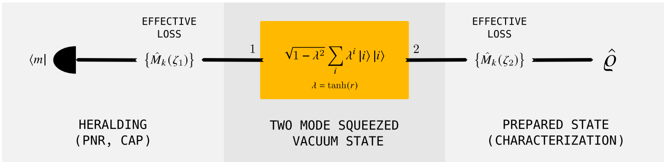
[1] Francesca Sansavini. Time and Frequency Multiplexing for Continuous-Variable Quantum Networks. Quantum Physics [quant-ph]. Sorbonne Université; Helsingin yliopisto (Finland), 2023. English. NNT : 2023SORUS64. tel-04521754

Towards optical states of four photons

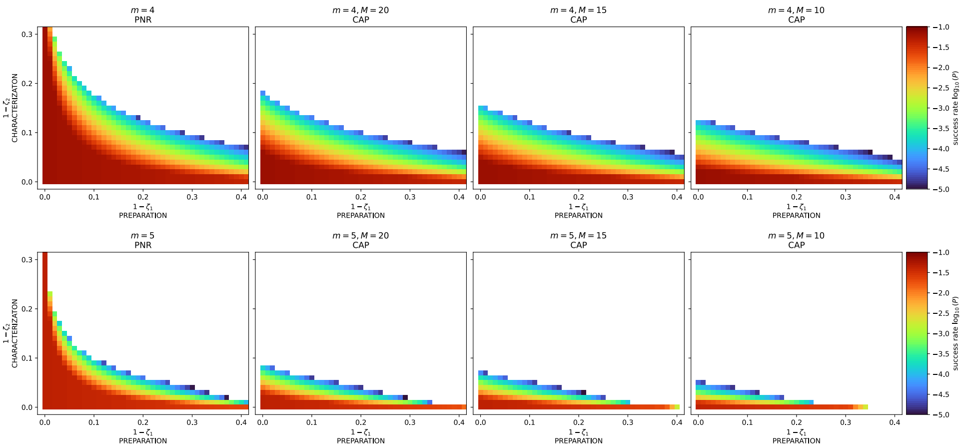
Jan Provazník

Department of Optics, Palacký University, 17. listopadu 1192/12, 771 46 Olomouc, Czech Republic

Quantum non-Gaussian states of traveling light fields are crucial components of quantum information processing protocols; however, their production is experimentally challenging. In this presentation, we discuss the minimal requirements imposed on the quantum efficiency of photon number resolving detectors and the quality of the squeezing operation in an experimental realization of certifiable quantum non-Gaussian states of individual photonic states with four and five photons.



The theoretical model of the experimental state preparation procedure is build around a two-mode squeezed vacuum state, where one of the modes is measured using a photon number resolving (PNR) detector, thus heralding a successful preparation of the desired state. Both true PNR detectors and their approximations based on cascaded avalanche photodiode (CAP) detectors [2] are considered. The nature of the prepared optical states is certified using a stellar rank witness based on the hierarchical criteria of genuine quantum non-Gaussianity [1].



The tolerable loss in preparation of certifiable genuine 4-photon (upper row) and 5-photon (lower row) quantum non-Gaussian states. Individual tiles represent the best attainable probability of success. Values in each tile are obtained by maximizing the probability of successfully preparing a certifiable state over the initial squeezing rate $0 \leq r \leq 10$dB. White tiles correspond to statistically insignificant cases with probabilities of success below 10^{-5}. The results obtained for a true PNR detector are presented in the leftmost column, while the remaining columns represent CAP detectors with $n = 20, 15$, and 10 constituent avalanche detectors.

References

[1] Lukáš Lachman et al. "Faithful Hierarchy of Genuine n-Photon Quantum Non-Gaussian Light". In: *Physical Review Letters* 123.4 (July 2019). DOI: 10.1103/physrevlett.123.043601.

[2] H. Paul et al. "Photon Chopping: New Way to Measure the Quantum State of Light". In: *Physical Review Letters* 76.14 (Apr. 1996), pp. 2464–2467. DOI: 10.1103/physrevlett.76.2464.

Entangling Mechanical Motion of Levitated Nanoparticles by Wave-Packet Dispersion

A. Rakhubovsky[1], **R. Filip**[1]

[1] *Department of Optics, Palacky University, 17. listopadu 1192/12, 779 00 Olomouc*

Levitated nanoparticles attracted significant interest thanks to promising applications in sensing and fundamental science tests. Ground-state cooling and coherent coupling of multiple nanoparticles' motion have been shown recently. One crucial difference of the nanoparticles from the traditional clamped mechanical resonators is the possibility to adjust the potential of the mechanical motion as the potential itself is defined by highly controllable tweezer field. In particular, it is possible to alternate harmonic-oscillator motion with the free motion, using the latter for nearly unitary expansion of the nanoparticles' wave packet which results in quantum squeezing of the mechanical motion. Here, we show that combining the free-fall-induced squeezing with the coupling of multiple nanoparticles can lead to the quantum entanglement between the nanoparticles. We evaluate the attainable entanglement in the presence of the relevant sources of decoherence and prove that the entanglement is achievable in state-of-the-art experiments.

Quantum enhanced absorption estimation with correlation assisted conditional states

N. Samantaray[1], **M. DAngelo**[1] **and J. G. Rarity**[2]

[1] *Dipartimento Interateneo di Fisica, Universit'a degli Studi di Bari, Via Giovanni Amendola,173, Bari, 70125, Italy*

[2] *Quantum Engineering Technology Labs, H. H. Wills Physics Laboratory and Department of Electrical and Electronic Engineering, University of Bristol, BS8 1FD, UK*

We have studied two different types of conditional states prepared from the twin beam states, i.e., when multiple photons are subtracted and detected from the idler respectively, and demonstrated their quantum advantage for absorption estimation over coherent and thermal states in both with and without per photon exposure scenarios. Photon subtraction is experimentally implemented by placing a low reflective beam splitter on the idler beam and single-photon avalanche diode in multiplex at the reflective port; clicks registered at the detector confirm photon subtraction. The conditional state prepared experimentally for the latter type, also known as heralding, for the single photon case shows sub-shot noise advantage.

In this work, we have theoretically obtained Wigner distribution function of these conditional states as probe passing through an absorbing sample which can be analogously obtained experimentally by performing Homodyne measurements. Analytically finding close form expression of marginals of quantum states other than photon number states is not so easy task. We have calculated marginal probability from the measured Wigner distribution which carries object information and subsequently Fisher information is calculated from the marginals. Conditional state for the subtraction case at low mean number of photons resemble high Fock states with increase in the number of annihilated photons, whereas heralding results in an incoherent mixture of thermal states whose phase space distribution appears closer to Fock states compared to the former. Results for the subtraction case show remarkable quantum advantage over coherent and thermal states at low light illumination and a comparison of the performance with respect to heralding will also be presented. It is evident that coherent states outperform photon annihilated states at high losses as expected. In contrast to joint photon number difference measurement which is difficult to maintain outside of laboratory set up, our approach does not require it, so it may be useful for long range absorption estimation of low absorbing objects.

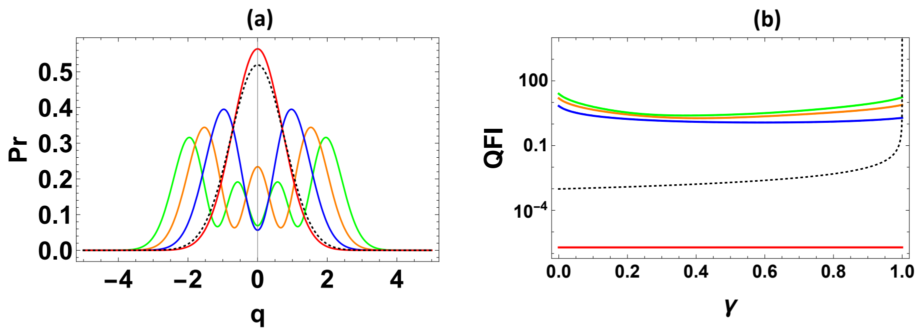


FIG. 1:Blue, orange and green curves correspond to one, two and three photon annihilated twin beam state respectively. Red, and black dotted curves show the performance of thermal and coherent state respectively. Average number of photon per mode is 0.1 and the detection loss is 2%: (a) Marginal probability as a function of position quadrature, (b) Fisher information versus absorption coefficient γ of the sample.

References

[1] J. Chesterking, Phys. Rev. Appl. **8**, 049902 (2017).

[2] H. Yang, Phys. Rev. Appl. **18**, 034021 (2022).

Detecting entanglement in a locally randomised measurements scenario

Gniewomir Sarbicki

Insitute of Physics, Nicolaus Copernicus University, Grudziadzka 5-7, 87-100 Toruń, Poland

Giovanni Scala[1,2], Anindia Bera[3]

[1] *INFN, Sezione di Bari, 70126 Bari, Italy*
[2] *Dipartimento Interateneo di Fisica, Politecnico di Bari, 70126 Bari, Italy*
[3] *Birla Institute of Technology Mesra, Jharkhand, India*

Randomised measurements scheme is used when the measuring party cannot trust its devices (local basis). In the scenario containing many spatialy-separated parties, sharing an entanglement state, we will explain what local invariants one can extract from experimental data in the framework of randomised measurements and show the examples of entanglement criteria expressible in terms of these invariants.

Exploring Quench Dynamics and Two-Particle Physics in a Topologically Non-Trivial Kronig-Penney Type Model

Sarika Sasidharan Nair[1], Giedrius Zlabys[1], Wen-bin He[1], Thomas Fogarty[1], Tomoki Ozawa[2] and Thomas Busch[1]

1 Quantum Systems Unit, Okinawa Institute of Science and Technology Graduate University, Onna-son, Okinawa 904-0495, Japan

2 Advanced Institute for Materials Research (WPI-AIMR), Tohoku University, Sendai 980-8577, Japan

Ultracold atoms are an excellent platform for testing various quantum models that are challenging to implement with conventional condensed matter systems. Advancements in cold atom physics have made it possible to create subwavelength nanoscale potentials, which facilitate strong atomic interactions. This allows for the realization of the Kronig-Penney model and its variations [1,2]. By introducing a periodic lattice shift in the nanoscale barriers within a finite-sized box, we can observe topologically protected edge states [3]. In this system, we investigate the non-equilibrium dynamics of a ground-state fermionic many-body gas after a quench between different lattice shifts. We focus particularly on the role of the chiral edge states intrinsic to the system. As part of our analysis, we calculate the overlaps of the ground states after the quench and demonstrate that the characteristic monotonic decay of the orthogonality catastrophe, which usually occurs with increasing system size, is notably altered [4]. We show that at the zero temperature, dynamics are influenced not just by the total particle number but rather by the number of occupied single-particle edge states. This behavior is further shown through an examination of the full work probability distribution, which provides a deeper understanding of the system's dynamics. Additionally, we explore the physics of two particles, considering scenarios both with and without contact interactions in this potential.

References

[1] M. L¸acki, M. A. Baranov, H. Pichler, and P. Zoller, Nanoscale "Dark State" Optical Potentials for Cold Atoms, Phys. Rev. Lett. 117, 233001 (2016).

[2] Y. Wang, S. Subhankar, P. Bienias, M. L¸acki, T.-C. Tsui, M. A. Baranov, A. V. Gorshkov, P. Zoller, J. V. Porto,and S. L. Rolston, Dark State Optical Lattice with a Subwavelength Spatial Structure, Phys. Rev. Lett. 120, 083601 (2018).

[3] I. Reshodko, A. Benseny, J. Romh´anyi, and T. Busch, Topological States in the Kronig–Penney model with Arbitrary Scattering Potentials, New J. Phys. 21, 013010(2019).

[4] S. S. Nair, G. Zlabys, W.-B. He, T. Fogarty, and T. Busch, Quench Dynamics in Topologically Nontrivial Quantum Many-Body Systems, Phys. Rev. A 111, 033313(2025).

Realizing non-Hermitian dynamics in a quantum walk of structured light

P. Savarese[1], S. Bansal[1], M. G. Ammendola[1], L. Amato[1], R. Barboza[2], B. Piccirillo[1], F. Di Colandrea[1], L. Marrucci[1], F. Cardano[1]

[1] Dipartimento di Fisica. Università degli Studi di Napoli Federico II, Complesso Universitario di Monte Sant'Angelo, Via Cintia, Napoli, Italy
[2] Dipartimento di Scienze e Ingegneria della Materia, dell'Ambiente ed Urbanistica, Università Politecnica delle Marche, Via Brecce Bianche, 60131 Ancona, Italy

In recent years, non-Hermitian photonics collected significant attention as a rising field in optics due to the emergence of numerous physical concepts and novel effects [1]. Unlike systems described by a Hermitian Hamiltonian, where the Hermitian conjugate ensures system closure to the environment and energy conservation, a non-Hermitian system characterized by complex eigenvalues enables the description of open systems and facilitates understanding of how a system can interact with the environment.
Here, we propose an innovative approach for simulating non-Hermitian dynamics by realizing a non-unitary photonic quantum walk based on a light beam propagating in free space and manipulated via step operators acting jointly on its polarization and transverse momentum [2]. Within this framework, we use the latter degrees of freedom to encode the coin and walker systems, respectively, typically characterizing coined quantum walks. To induce spin-rotation, we utilize a uniform liquid-crystal (LC) plate and an LC dichroic polarization grating to obtain a spin-dependent non-unitary translation operation on the walker [3]. Through the combination of liquid crystals and absorbing dyes, we can manipulate both polarization and light. These tunable devices enable precise control over system losses and allow us to explore different dynamical regimes. We investigate multiple configurations by varying the input states and evolution operators, tailoring them through the effects of birefringence and dichroism on the system. The realized system is shown in Figure 1 [4].

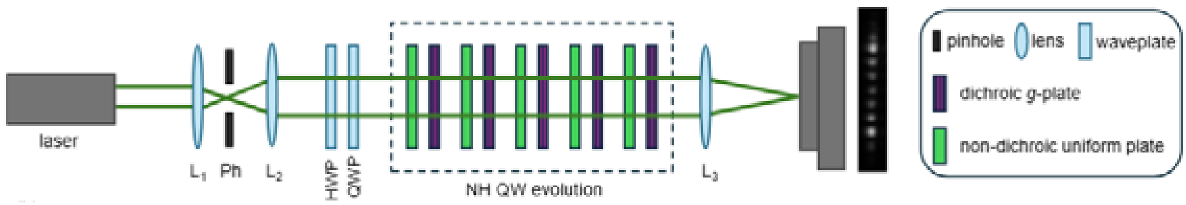


Figure 1. Sketch of the experimental setup. A Gaussian beam is expanded and filtered using a telescopic lens system (L1-L2) and a pinhole (Ph). Its polarization is controlled via a half-wave plate (HWP) and a quarter-wave plate (QWP). It passes through dichroic LC metasurfaces and uniform plates, implementing the dynamics. The output modes form Gaussian spots in the focal plane, enabling probability distribution extraction.

We validate our platform across a variety of configurations by measuring the similarity between the theoretical and experimental probability distribution, which consistently remains above 97%.

References

[1] Okuma, Nobuyuki, and Masatoshi Sato. "Non-Hermitian topological phenomena: A review." *Annual Review of Condensed Matter Physics* 14.1 (2023): 83-107.

[2] Di Colandrea, Francesco, et al. "Ultra-long quantum walks via spin–orbit photonics." *Optica* 10.3 (2023): 324-331.

[3] Savarese, Paola et al. "Electrically tunable liquid-crystal metasurfaces with patterned birefringence and dichroism." *arXiv preprint arXiv:2501.17680* (2025).

[4] Savarese, Paola, et al. "Programmable non-Hermitian photonic quantum walks via dichroic metasurfaces." *arXiv preprint arXiv:2503.05072* (2025).

Dynamics of open quantum systems with initial system-environment correlations via stochastic unravelings

F. Settimo[1], K. Luoma[1], D. Chruściński[2], A. Smirne[3,4], B. Vacchini[3,4], J. Piilo[1]

[1] *Department of Physics and Astronomy, University of Turku, FI-20014 Turun yliopisto, Finland*
[2] *Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziadzka 5/7, 87-100 Toruń, Poland*
[3] *Dipartimento di Fisica "Aldo Pontremoli", Università degli Studi di Milano, Via Celoria 16, I-20133 Milan, Italy*
[4] *Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Via Celoria 16, I-20133 Milan, Italy*

In standard treatments of open quantum systems, the reduced dynamics is described starting from the assumption that the system and the environment are initially uncorrelated. However, this assumption is not always guaranteed in realistic scenarios, and several theoretical approaches have been introduced to characterize initially correlated dynamics. For the uncorrelated scenario, stochastic unravelings are a powerful tool to simulate the dynamics, but so far no methods to apply them in the most general case in which correlations are initially present have been proposed. In our work [1], we developed a way to generalize such stochastic methods to the most general case in which the open system and the environment are initially correlated. We do so starting from the bath positive (B+) or one-sided positive decomposition (OPD) formalism [2], providing a framework that is compatible for any unraveling scheme, both diffusive and piecewise deterministic. In particular, we employ the recently developed generalized rate operator [3], which allows us to unravel some non-Markovian dynamics without the need of reverse jumps. This generalization allows not only for more powerful simulations for the reduced dynamics but also for a deeper theoretical understanding of open system dynamics.

[1] Settimo, F., Luoma, K., Chruściński, D., Smirne, A., Vacchini, B., & Piilo, J. (2025). Dynamics of Open Quantum Systems with Initial System-Environment Correlations via Stochastic Unravelings. arXiv:2502.12818.

[2] Paz-Silva, G. A., Hall, M. J. W., & Wiseman, H. M. (2019). Dynamics of initially correlated open quantum systems: Theory and applications. *Physical Review A*, 100(4), 1–19.

[3] Settimo, F., Luoma, K., Chruściński, D., Vacchini, B., Smirne, A., & Piilo, J. (2024). Generalized-rate-operator quantum jumps via realization-dependent transformations. *Physical Review A, 109*(6), 062201.

PII-30

Environment-assisted generation of quantum correlations in open quantum systems

Stoica Alina-Alexandra[1], Isar Aurelian[1]

[1] *National Institute of Physics and Nuclear Engineering, Reactorului 30, RO-077125, Bucharest-Magurele, Romania*

Hellinger geometric quantum discord and interferometric power are analyzed for an open system consisting of two bosonic modes, while interacting with four different environments: vacuum, squeezed vacuum, thermal and squeezed thermal, taking the initial state of the open system to be either a single-mode squeezed state, which presents no initial correlations or a squeezed vacuum state. The description of the evolution of the correlations is formulated in the framework of the theory of open systems, based on completely positive quantum dynamical semigroups, using the Gorini-Kossakowski-Lindblad-Sudarshan equation. We showed that both quantum correlations can be generated from an initial factorized state and even amplified, while also studying the back and forth impact of the squeezing parameters on the considered correlations. For certain environments, the difference between the squeezing of the initial state and the squeezing of the environment can either destroy the correlations or enhance them. We also studied the presence of decoherence free states (DFS) if initial parameters are chosen suitably.

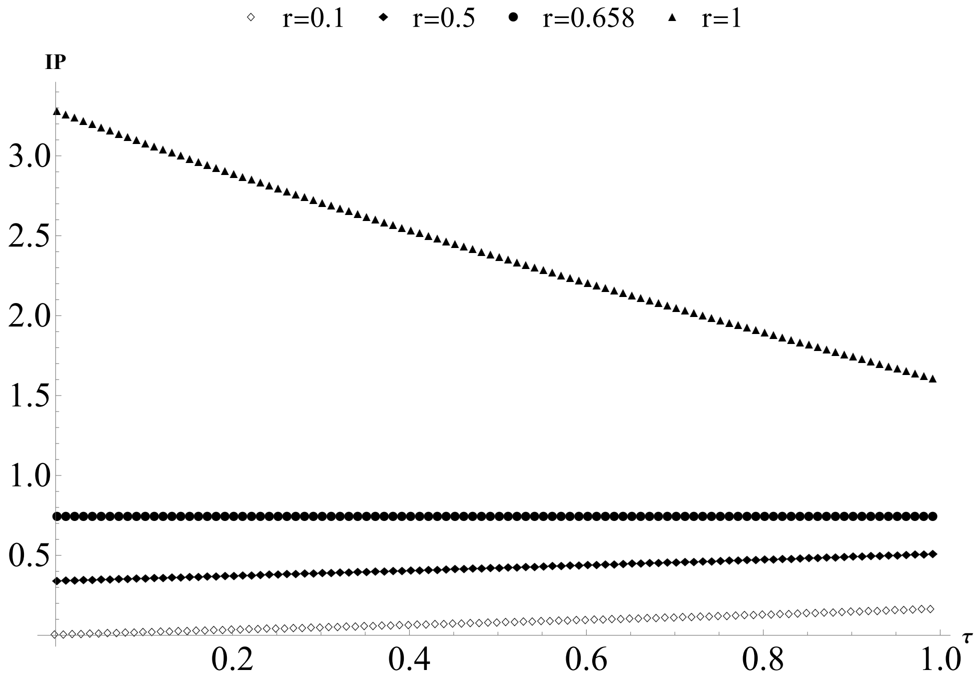


FIG. 1: Interferometric power over time τ for different initial squeezing parameters r.

References

[1] A. Stoica, A. Isar, TBP

[2] X. Yang, G.H. Huang, M.F. Fang, Optics Comm 341, 91-96 (2015)

[3] S.H. Xiang, B. Shao, K.H. Song, Phys. Rev A 78, 052313 (2008)

[4] G. Adesso, Phys. Rev. A 90, 022321 (2014)

[5] G. Adesso, D. Girolami, Int. J. Q. Information 9 (2011), 1773.

[6] P. Marian, T. A. Marian, J. Phys. A: Math. Theor. 48, 115301 (2015)

Continuous-variable Unitary Averaging Protocol

S. Nibedita Swain[1,2,3], Ryan J. Marshman[3], Timothy C. Ralph[3]

[1] *School of Mathematical and Physical Sciences, University of Technology Sydney, Ultimo, NSW 2007, Australia*

[2] *Sydney Quantum Academy, Sydney, NSW 2000, Australia*

[3] *Centre for Quantum Computation and Communication Technology, School of Mathematics and Physics, University of Queensland, Brisbane, Queensland 4072, Australia*

A significant hurdle for quantum communication and processing using bosonic systems is stochastic phase errors which occur as the photons propagate through a channel. These errors will reduce the quality of output states passing through the channel and therefore reduce the channels capacity. We present a scheme of continuous-variable unitary averaging (CVUA) for protecting unknown Gaussian states transmitted through an optical channel (L.H.S, Fig.1). The scheme reduces the effect of phase noise on fidelity, thereby enhancing the channel via a probabilistic-error-correcting protocol. The scheme is robust to loss and typically succeeds with high probability. We provide numerical simulations and analytical approximations based on realistic technological parameters and analyse the protocol's asymptotic behaviour, emphasising its immediate relevance for quantum communication [1].

We applied this model to a practical continuous-variable quantum key distribution system, demonstrating an enhancement in key rates in a heralded manner. Additionally, we extend the protocol to multi-mode systems with arbitrary unitary noise (R.H.S, Fig.1) to achieve high-quality multi-mode states with a sufficient success probability to potentially enhance optical quantum computing [2].

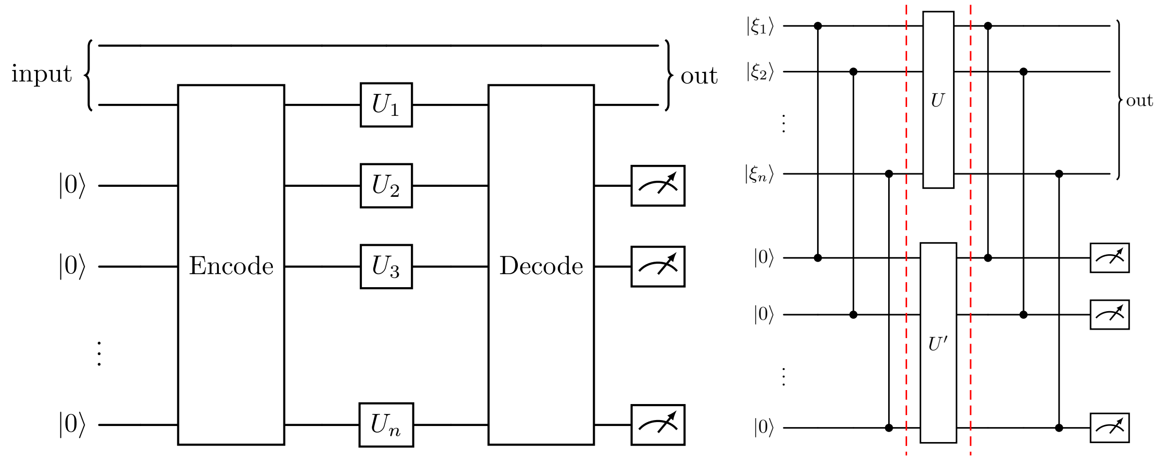
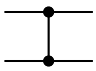
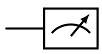


Figure 1: L.H.S,- A passive unitary averaging scheme utilises a beam splitter network for redundant encoding over n modes. One mode of a two-mode state is evenly distributed across n transmission modes. Each mode undergoes independent single-mode unitary noise. The decoding network reverses the encoding process, and upon heralding $n-1$ error modes in the vacuum state, the output state exhibits reduced noise. R.H.S,- Multi-mode CVUA. In both the encoding and decoding stages, 50:50 beamsplitters are used. The operations U and U' represent arbitrary interferometers. Finally, vacuum is detected in the $n-m$ mode to obtain multi-mode output with reduced noise.  and  represent 50:50 beamsplitter and vacuum detection respectively.

References

[1] SN Swain et.al., Phys. Rev. A **110**, 032622 (2024).

[2] SN Swain et.al., arXiv:2506.05732 (2025)

PII-32

Generation of multiphoton states by multiplexing of heralded photon sources

B.M. Szilasi[1,2], M. Mechler[1,2], P. Adam[1,2]

[1] *Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, P.O. Box 49, H-1525 Budapest, Hungary*
[2] *Institute of Physics, University of Pécs, Ifjúság útja 6, H-7624 Pécs, Hungary*

Recent experiments aiming at studying phenomena in the fields of quantum information processing and photonic quantum technology require the development and improvement of reliable on-demand multiphoton sources. An experimentally realizable technique of the generation of multiphoton states is based on heralded photon sources, where photon pairs are generated in two modes in some nonlinear optical processes. The detection of a given number of photons by a photon-number-resolving detector in the idler mode heralds the presence of the corresponding multiphoton state in the signal. This technique has been efficiently applied for single-photon generation. The multiphoton noise of heralded single-photon sources originating from the probabilistic nature of the pair generation can be minimized by multiplexing [1, 2]. In the case of spatially multiplexed single-photon sources, several heralded sources are applied in parallel. Decreasing the mean photon numbers of the generated photon pairs in each sources in combination with the application of several sources ensures the high single-photon probability with low multiphoton contribution. Using the statistical theory of these sources developed recently, both the input mean photon number and the number of the multiplexed sources can be optimized [3–6].

In this work, we propose spatially multiplexed heralded multiphoton sources to generate multiphoton states. We consider multiphoton sources based on minimum-based, maximum-logic output-extended incomplete binary-tree multiplexers built of asymmetric photon routers [6]. We optimize the performance of this system using the extension of the method applied earlier for the optimization of spatially multiplexed single-photon sources. We show that, using the proposed scheme, it is possible to generate multiphoton states up to $n = 5$ photons with considerably higher multiphoton probabilities than the one that can be achieved with a single heralded multiphoton source. We analyze the performance of the proposed spatially multiplexed multi-photon sources assuming two-photon output states for a wide range of the loss parameters characterizing the system. We show that the proposed system can be used to generate few-photon states with high probabilities, even for suboptimal system sizes.

[1] E. Meyer-Scott, C. Silberhorn, A. Migdall, Rev. Sci. Instrum. **91**, 041101 (2020).

[2] P. Adam, M. Mechler, Appl. Sci. **14**, 11249 (2024).

[3] F. Bodog, M. Mechler, M. Koniorczyk, P. Adam, Phys. Rev. A **102** 013513 (2020).

[4] P. Adam, F. Bodog, M. Mechler, Opt. Express **30** 6999 (2022).

[5] P. Adam, F. Bodog, M. Koniorczyk, M. Mechler, Phys. Rev. A **105** 063721 (2022).

[6] P. Adam, M. Mechler, Opt. Express **31**, 30194 (2023).

Some non-algebraic forms of $\exp(\hat{A}+\hat{B})$

Marco A. Tapia-Valerdi

Instituto Nacional de Astrofísica Óptica y Electrónica (INAOE)
Luis Enrique Erro 1, Santa María Tonantzintla, Puebla, 72840, Mexico

M. A. Tapia-Valerdi[1], I. Ramos-Prieto[1], F. Soto-Eguibar[1], H. M. Moya-Cessa[1]

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

In quantum mechanics, the solutions to many physical evolution equations often take the form of an exponential function involving two or more operators acting on a given initial condition; thus, it is frequently necessary to find expressions for $\exp(\hat{A}+\hat{B})$. When the operators $\hat{A}$ and $\hat{B}$ commute, Lie algebra methods are commonly employed to explore non-classical light behaviors in quantum optical systems. However, for non-commuting operators, this problem becomes complex or even impossible. In this work, we present cases where $\exp(\hat{A}+\hat{B})$ can be explicitly factored, even though operators (or superoperators) $\hat{A}$ and $\hat{B}$ do not commute in a conventional manner. Our factorization approach is applied to a Lindblad operator modeling single-photon decay and a binary Glauber-Fock photonic lattice.

References

[1] L. Teuber and S. Scheel, Phys. Rev. A 101, 042124 (2020).

[2] J. Wei and E. Norman, J. Math. Phys. 4, 575 (1963).

[3] W. Rossmann, Lie Groups: An Introduction Through Linear Groups (Oxford University Press, 2002).

[4] B. C. Hall, Lie Groups, Lie Algebras, and Representations (Springer New York, 2013).

Quantum-Chemical Model of the Optical Methanol-Sensing Mechanism of the *meso*-Formyl BODIPY Compounds

S. Toliautas[1], **D. Palinauskas**[1]

[1]*Vilnius University, Faculty of Physics, Institute of Chemical Physics*

Molecular compounds based on the boron-dipyrromethene (BODIPY) group have been shown to have promising potential for use as microscopic, single-molecule scale optical (fluorescence lifetime-based) sensors of environment properties, such as temperature or viscosity. These compounds can exhibit complex energy-relaxation behavior depending on the surroundings, which necessitates both experimental and theoretical research of their own properties [1].

A recent study demonstrated how a *meso*-formyl BODIPY derivative (Fig. 1) could act as an optical sensor for cellular viscosity and methanol concentration in the molecule's vicinity. However, an attempt to increase the fluorescence wavelength – by changing the molecular structure – for better compatibility with biological samples resulted in the loss of both polarity (including methanol concentration) and viscosity sensitivity [2].

In this work, a theoretical investigation of the potential energy surface properties of *meso*-formyl BODIPY variants in methanol [3] is continued, applying an existing quantum-chemical model of microviscosity sensitivity (adjusted to include direct interaction with methanol and possible hemiacetal formation) and further estimating the effects of the non-adiabatic coupling on the photo-induced fluorescence of the compounds.

The research is supported by the Research Council of Lithuania (LMT grant no. S-MIP-23-48). Quantum-chemical computations were performed using resources at the supercomputer "VU HPC" of Vilnius University in the Faculty of Physics location.

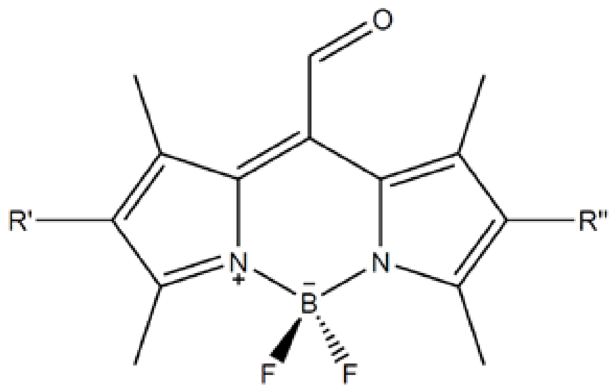


FIG. 1: Chemical structure of *meso*-formyl BODIPY derivatives.

References

[1] A. Polita *et al.*, Phys. Chem. Chem. Phys. **22**, 8296 (2020).
[2] R. Žvirblis *et al.*, in *Open Readings* (Vilnius, 2022).
[3] D. Palinauskas *et al.*, in *Nordic Baltic Femtochemistry* (Tartu, 2024).

Resource-efficient quantum correlation measurement using a multi-copy estimation approach

Patrycja Tulewicz[1,2], Davide Ferrari[2], Michele Amoretti[2], Karol Bartkiewicz[1,3],Adam Miranowicz[1], 3,Franco Nori[3], 4, 5

[1] *Institute of Spintronics and Quantum Information, Adam Mickiewicz University, PL-61-614 Poznań, Poland*
[2] *Quantum Software Laboratory, University of Parma, 43124 Parma, Italy*
[3] *Theoretical Quantum Physics Laboratory, Cluster for Pioneering Research, RIKEN, Wakoshi, Saitama 351-0198, Japan*
[4] *Center for Quantum Computing, RIKEN, Wakoshi, Saitama 351-0198, Japan* [5] *Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1040, USA*

Measuring complex properties in quantum systems, such as entanglement and Bell's nonlocality, typically requires resource-intensive methods such as quantum state tomography (QST). These traditional methods require resources that grow exponentially with the size of the system, making QST particularly difficult to apply to large quantum systems.

I would like to present a multi-copy estimation (MCE) technique that allows direct measurement of quantum correlations with significantly reduced resource consumption. By using multi-copy measurements in conjunction with artificial neural networks, our technique achieves a 67% reduction in measurement requirements compared to QST, while maintaining accuracy. We demonstrate the usefulness of the method through both theoretical and experimental verifications on an IBM quantum processor and find that MCE is much more insensitive to noise than conventional methods.

The MCE approach uses specific singlet projection measurements on multiple copies of the quantum state to obtain key information about entanglement, as well as Bell's nonlocality. Using maximum likelihood estimation (MLE) and SHapley Additive exPlanations (SHAP) analysis, we identify a minimum of just five key measurements that provide reliable estimates of quantum correlation measures. This approach proves particularly valuable for describing quantum properties in noisy regimes.

As an application, I will show how MCE can be used for benchmarking in distributed quantum computing (DQC) systems, by evaluating the entanglement behavior in different network topologies. The method provides an excellent representation of how factors such as the number of entangled nodes and gate errors affect quantum correlations in network scenarios, providing important insights for optimizing quantum network designs.

Our research represents a significant step toward resource-efficient quantum characterization techniques, providing practical techniques for quantifying quantum correlations in current and future quantum systems where measurement resources are limited and noise is unavoidable [1].

References

[1] P. Tulewicz, K. Bartkiewicz, A. Miranowicz, and F. Nori, Resource-Efficient Quantum Correlation Measurement: A Multicopy Neural Network Approach for Practical Applications (2024). arXiv:2411.05745

[2] D. Ferrari, S. Carretta, and M. Amoretti, A Modular Quantum Compilation Framework for Distributed Quantum Computing, IEEE Transactions on Quantum Engineering, vol. 4, 2023

[3] D. Ferrari and M. Amoretti, A Design Framework for the Simulation of Distributed Quantum Computing, in *Proceedings of the 2024 Workshop on High Performance and Quantum Computing Integration*, ACM, 2024, pp. 4–10, `https://doi.org/10.1145/3659996.3660035`

Acknowledgements: This work was funded by the Polish National Science Center from funds awarded through the Maestro Grant No. DEC-2019/34/A/ST2/00081, and the European Union's Horizon Europe research and innovation programme under grant agreement No. 101102140 – QIA Phase 1.

Single-qubit probes for temperature estimation in the presence of collective baths

Asghar Ullah[1], Marco Cattaneo[2], Özgür E. Müstecaplıoğlu[1]

[1] *Department of Physics, Koç University, 34450 Sarıyer, Istanbul, Türkiye*
[2] *QTF Centre of Excellence, Department of Physics, University of Helsinki, P.O. Box 43, FI-00014 Helsinki, Finland*

We study the performance of single-qubit probes for temperature estimation in the presence of collective baths. We consider a system of two qubits, each locally dissipating into its own bath while being coupled to a common bath. In this setup, we investigate different scenarios for temperature estimation of both the common and local baths. First, we explore how the precision of a single-qubit probe for the temperature of the common bath may be enhanced by the collective effects generated by the bath itself, if the second qubit is in resonance with the probe. We also analyze how the presence of additional local baths on each qubit may jeopardize, or improve, this result. Next, we show that one qubit may serve as a probe to measure the temperature of the local bath, affecting the other qubit by exploiting their interaction mediated by the common bath. This approach enables remote temperature sensing without directly coupling the probe to the target qubit or its local environment, thereby minimizing potential disturbances and practical challenges. However, in the absence of a direct qubit-qubit coupling, this protocol works only for very high temperatures of the local bath whose temperature we aim at estimating.

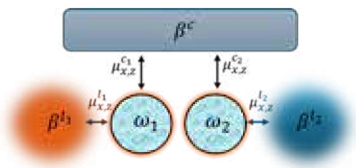


FIG. 1: Two qubits interacting with thermal baths labeled by the inverse temperatures β^c, β^{l_1}, and β^{l_2}, corresponding to the common bath, the local bath on the first qubit, and the local bath on the second qubit, respectively.

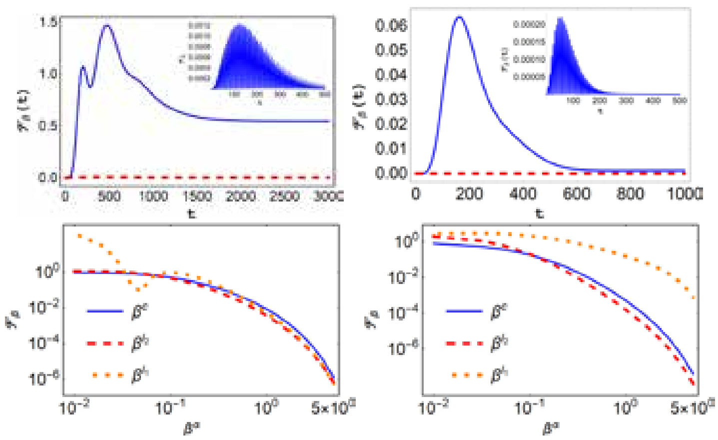


Figure 1: **Top panel:** QFI as a function of time t for the estimation of the local bath temperature β^{l_1} (blue curve) and β^{l_2} (red curve), for small detuning ($\omega_- = 0.01$) and $k = 0$. **(a)** QFI in the steady state of a single-qubit reduced density matrix as a function of the inverse temperature β^α, where $\alpha = l_1, l_2, c$ for two uncoupled qubits ($k = 0$) and $k = 10^{-1}$.

References

[1] A. Ullah, M. Cattaneo, and Ö. E. Müstecaplıoğlu, arXiv:2502.17197 [quant-ph] (2025).

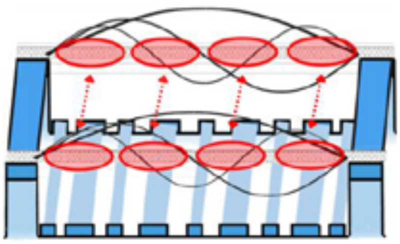
[2] M. Cattaneo, G. L. Giorgi, S. Maniscalco, and R. Zambrini, New J. Phys. **21**, 113045 (2019).

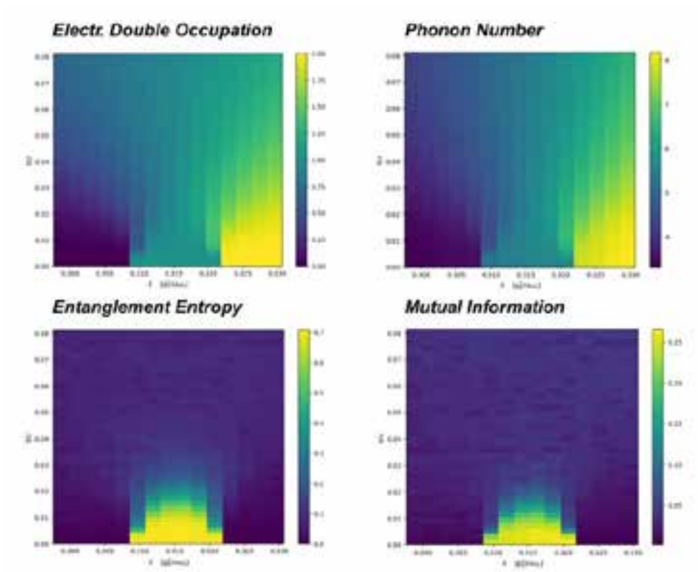
Phonon-Induced Electronic Bell State in a Two-Dimensional Quantum Dot Quantum Simulator

D. Ullrich[1], **A. Sanpera**[1,2]
[1]*Física Teòretica: Informatió i Fenòmens Quàntics. Departnement de Física Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain*
[2]*ICREA, Pg. Lluís Companys 23, 08010 Barcelona, Spain*
(Dated: March 31, 2025)

We report on the different phases encountered when two suspended nanotubes, each hosting several quantum dots occupied by electrons, are coupled electrostatically. The proposed system is a two-dimensional extension of the one proposed in [1]. Each carbon nanotube is characterised by four quantum dots and four unpolarized electrons occupying the latter. Via gate electrodes, the electrons couple to the flexural modes of the tube resulting in a competition between the repulsive electron-electron interaction and the attrictive interaction mediated by the phonons. In the strong coupling regime, the system shows a transition from a Mott insulating state to a polaronic state. Additionally, the system goes into a non-local state for greater tunnelling amplitudes characterised by charge and phononic correlations. We extend these results by computing the entanglement entropy between electrons and phonons showing non-zero values at the transition to the non-local regime.

Our original contribution is the study of the phase spectrum for a system of two parallel nanotubes. Each of them having the same characteristics as the previous single tube. They are further coupled via a Coulomb potential between opposing quantum dots. Our findings show the three previously mentioned phases in addition to a new intermediate phase in the zero-tunneling limit generated by the electrosatic interaction. This phase is characterised by non-zero values of the entanglement entropy between the two subsystems and the mutual information between the phonons of the different tubes. These classical and quantum correlations are the result of the ground state being a superposition of one tube being in a Mott and the other in a paired state equivalent to an electronic Bell state. To be able to nummerically simulate such a complex system, we have turned to a hypothetical system of lower phonon numbers which we show has an identical spectrum except for a compression on the t-axis. Further, we have restricted ourselves to a single phononic mode model which can be realised by exponentially surpressing all other modes via Bose-Einstein condensation.





References:

[1] Bhattacharya, U., Grass, T., Bachtold, A., Lewenstein, M. & Pistolesi, F. Phonon-Induced Pairing in Quantum Dot Quantum Simulator. *Nano Lett.* 21, 9661–9667 (2021)

PII-38

Superconducting YBCO planar microresonators for conventional high sensitivity ESR

<u>G. Usevičius</u>[1], O. W. Kennedy[2], I. Pocius[1], P. Hogan[2], A. V. R. de Temino[2], J.-B. Verstraete[2], G. A. Jacob[2], J. Alexander[2], V. Kalendra[1], J. Banys[1], John J.L. Morton[2,3], M. Šimėnas[1]

[1]*Faculty of Physics, Vilnius, University, Sauletekio 3, LT-10257 Vilnius, Lithuania*
[2]*London Centre for Nanotechnology, University College London, London WC1H 0AH, UK*
[3]*Dept. of Electronic & Electrical Engineering, University College London, London WC1E 7JE, UK*

Electron spin resonance (ESR) is a powerful spectroscopic technique with applications covering structural biology [1], spin-based quantum technologies [2,3], solid-state physics [4], and other important fields [5]. Despite its versatility, the relatively low sensitivity of conventional ESR poses a significant challenge for studying volume-limited systems, as standard ESR resonators often require samples of microliter volume to achieve detectable spin signals (13). To overcome these limitations, considerable effort has been directed toward the development of planar microwave microresonators of various designs.

Here, we introduce a yttrium barium copper oxide (YBCO) microresonator design (**FIG. 1A**) along with a simple approach to microresonator coupling via a standard 3D ESR resonator which together offer the advantages of high-spin number sensitivity with the ability to be readily deployed within any typical ESR laboratory. The microresonator features a spiral geometry designed for X-band (9.5 GHz) ESR with a mode volume of about 7 nL, which provides a 1,000 fold increase in the spin number sensitivity.

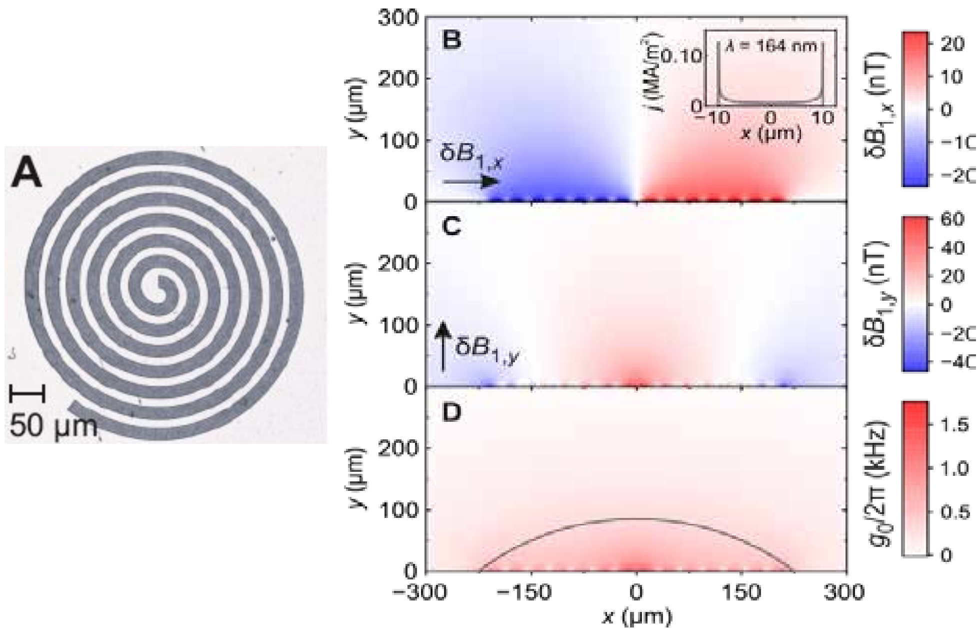


FIG. 1: (**A**) Fabricated planar YBCO spiral microwave microresonator on a sapphire substrate.Spatial distribution of vacuum magnetic field fluctuations (**B**) $\delta B_{1,x}$ and (**C**) $\delta B_{1,y}$ of a spiral microresonator corresponding to the current vacuum fluctuations at 10 K (inset shows the current profile) as obtained from COMSOL simulations. (**D**) Spatial distribution of the calculated spin-resonator coupling strength g_0 for spin species with g-factor of 2. The curve indicates cross section of a spherical cap representing the microresonator mode volume.

References

[1] G. Jeschke, DEER Distance Measurements on Proteins. Annu. Rev. Phys. Chem. 63, 419–446 (2012).
[2] J. M. Zadrozny, J. Niklas, O. G. Poluektov, D. E. Freedman, Millisecond Coherence Time in a Tunable Molecular Electronic Spin Qubit. ACS Cent. Sci. 1, 488–492 (2015).
[3] A. Gaita-Ari˜no, F. Luis, S. Hill, E. Coronado, Molecular spins for quantum computation. Nat. Chem. 11, 301–309 (2019).
[4] G. D. Watkins, EPR of defects in semiconductors: Past, present, future. Phys. Solid State 41, 746–750 (1999).
[5] M. M. Roessler, E. Salvadori, Principles and applications of EPR spectroscopy in the chemical sciences. Chem. Soc. Rev. 47, 2534–2553 (2018).

Analytical solutions of the open dispersive Jaynes-Cummings model and open quantum Rabi model

A. Vaaranta[1,2], **M. Cattaneo**[1], **P. Muratore-Ginanneschi**[3]

[1] *QTF Centre of Excellence, Department of Physics, University of Helsinki, P.O. Box 43, FI-00014 Helsinki, Finland*
[2] *QTF Centre of Excellence, Department of Applied Physics, Aalto University, P.O. Box 15100, FI-00076 Aalto, Finland*
[3] *Department of Mathematics and Statistics, University of Helsinki, P.O. Box 68, FI-00014 Helsinki, Finland*

The Jaynes-Cummings and quantum Rabi models are fundamental to cavity and circuit quantum electrodynamics, as they describe the simplest form of light-matter interaction, where a single qubit is coupled to a single bosonic mode. A scenario that is commonly encountered in the experimental practice arises when the bosonic mode interacts with an external dissipative thermal bath, making the qubit-boson system open. In this work, we present new analytical solutions of the Lindblad master equations for the open dispersive Jaynes-Cummings and quantum Rabi models in the limit of weak qubit-boson coupling g, using the holomorphic formalism in Bargmann space. Specifically, we derive the most general solution of the local Lindblad master equation for the open dispersive Jaynes-Cummings model coupled to a thermal bath, with the only assumptions that the initial state of the qubit-boson system is separable. Additionally, we obtain a perturbative analytical solution for the open quantum Rabi model up to second order in g. Notably, our findings include a new formula for the qubit's steady state at zeroth order, showing a non-perturbative difference in the steady state populations of the quantum Rabi and Jaynes-Cummings models. The stationary populations depend on both qubit and boson frequencies in the quantum Rabi model, but not in the Jaynes-Cummings model. Our results are of general interest to the study of open quantum systems in the context of light-matter interaction.

References

[1] A. Vaaranta, M. Cattaneo, P. Muratore-Ginanneschi, Analytical solutions of the open Jaynes-Cummings and quantum Rabi models, arXiv:2411.18310 (2024).

The role of entanglement in the excitation of a three-level atom by a propagating two-photon light

Masood Valipour[1], Gniewomir Sarbicki[1], Karolina Słowik[1], Anita Dąbrowska[2]
[1] *Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziądzka 5/7, 87–100 Toruń, Poland*
[2] *Institute of Theoretical Physics and Astrophysics, Faculty of Mathematics, Physics and Informatics, University of Gdańsk, Wita Stwosza 57, 80–308 Gdańsk, Poland*

We considered the problem of optimal excitation of a three-level atom of ladder configuration by propagating light in the two-photon state [1]. The applied atom-light interaction model is based on the Wigner-Weisskopf approximation. Thus the model is formulated within the following assumptions: a flat coupling constant, rotating wave approximation, and the extension of the lower limit of integration over frequency to minus infinity [2, 3]. We analyze the probability of two-photon absorption by the atom using the analytical formula determined in [4] that was obtained by making use of quantum trajectories [2, 5]. We characterized the properties of the optimal two-photon state that excites an atom perfectly, i.e. with probability equal to one. The spectro-temporal shape of the optimal state of light is determined by the lifetimes of the atomic states, with the degree of photonic entanglement in the optimal state depending on the lifetime ratio. In consequence, two distinct interaction regimes can be identified in which the entanglement of the input state of light has a qualitatively different impact. We show that photon entanglement plays a fundamental role in the optimal excitation of a system by two-photon light.

As the optimal states may be challenging to prepare in general, we compare the results with those obtained for photon pairs that can be generated in the laboratory. We optimize the parameters of these two-photon light states to achieve the maximum probability of two-photon absorption for the atomic system. We present the role of entanglement and resonances in the atom excitation process, and show how destructive and constructive light interference affects excitation of the atom. Part of the obtained results has already been published and presented in [6]

[1] R. Loudon, *The Quantum Theory of Light*, third edition, (Oxford University Press, Oxford, 2000).
[2] C. W. Gardiner, P. Zoller, *Quantum noise*, Springer-Verlag, Berlin-Heidelberg (2010)
[3] M. O. Scully, M. S. Zubairy, *Quantum Optics*, Cambridge University Press, Cambridge (1997)
[4] A. Dąbrowska, G. Sarbicki, Quantum trajectories and output field properties for two-photon input field, arXiv:2409.07428
[5] H. M. Wiseman, G. J. Milburn, *Quantum measurement and control*, University Press, Cambridge (2010)
[6] M. Valipour, G. Sarbicki, K. Słowik, A. Dąbrowska, Optimization of two-photon absorption for a three-level atom, Phys. Rev. A 111, 033709, 2025

Enhanced linear optical state preparation with invariants

Pablo V. Parellada[1], Juan Carlos García Escartín[1]

[1] *Universidad de Valladolid, Dpto. Teoría de la Señal e Ing. Telemática, Spain*

Not all photonic states can be connected with a passive linear interferometer, which makes preparing arbitrary states challenging with linear optics. Many state preparation algorithms simply parametrize the unitary of an interferometer and optimize it to produce the desired state, which is computationally expensive. In this work, we use invariant quantities to reduce the cost of optimizing these state preparations. When a state preparation is allowed, some quantities of the input and output states are conserved (a necessary condition). This invariant conservation narrows the search space of possible unitaries, reducing the number of parameters from quadratic (in the best case) to no reduction (in the worst case). Once we have this parametrized unitary, we can apply the usual algorithms to optimize the preparation of the output state with a reduced cost. In addition to improving state preparation algorithms, this new parametrization may help to classify the equivalence classes of states connected via linear optics.

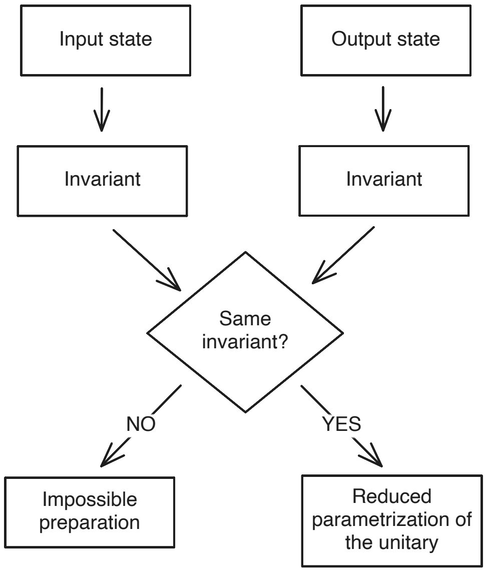


FIG. 1: State preparation flow diagram. First we check if the input and output invariants are equal. If they are not, we discard this preparation. If they are equal, we can parametrize a unitary that conserves the invariants, reducing the number of free parameters in the unitary.

References

[1] Pablo V. Parellada et al. *Lie algebraic invariants in quantum linear optics*. arXiv:2409.12223 [quant-ph]. 2024. URL: `http://arxiv.org/abs/2409.12223`.

[2] Pablo V. Parellada et al. "No-go theorems for photon state transformations in quantum linear optics". In: *Results in Physics* 54 (2023), p. 107108. DOI: `10.1016/j.rinp.2023.107108`.

Single-atom-based quantum jump detection of single photons in a broadband background

Laura Zarraoa[1] *, *Romain Veyron*[1], *Tomas Lamich*[1], *Morgan W. Mitchell*[1,2]

[1] *ICFO- The Institute of Photonic Sciences,* [2] *ICREA-Institucio Catalana de Recerca i Estudis Avancats*

(*) romain.veyron@icfo.eu

Interfacing individual particles of light and matter is a foremost goal in quantum technologies. Quantum jumps, i.e. abrupt changes of quantum state, in atoms can be used to herald a photon absorption. The abitlity to detect low light signals embedded in a broadband background is interesting for a growing number of applications that require high sensitivity and strong background rejection through frequency discrimination, for example free-space quantum communication in daylight or space classical communications. In [1], we demonstrate a narrowband quantum jump photodetector (QJPD) to detect single-photons based on a single cold atom and quantify its experimental performance. We introduce methodology, specific to the QJPD scenario, for determining the quantum efficiency (QE) and dark counts contributions in quantum jump photodetection. This system, similarly to CCD and CMOS detectors, has separated acquisition and readout time windows with distinct DC contributions. We demonstrate a QE of $2.9(2) \times 10^{-3}$ (a record for a single atom in free space), a readout contribution of $1.8(1) \times 10^{-2}$ counts per readout and a dark current of $9(20) \times 10^{-3}$ cps, consistent with zero and limited by measurement statistics. These dark counts are already competitive with any non-cryogenic detector. To quantify the background rejection capabilities of the QJPD, we measured a rejection factor of 10^6 in photon number by detecting a strongly attenuated laser at single photon levels on top of a broadband light source taken as the sunlight. Several proven atomic and optical technologies could be applied to reach different wavelength ranges, narrower bandwidths, higher quantum efficiency, and lower dark counts. Finally, we also used the QJPD scheme to detect single photons coming from a spontaneous parametric down conversion photon source. This opens the path to studying light-matter interaction between individual photons and atoms.

References

[1] L. Zarraoa, Phys. Rev. Research **6**, 033338 (2024).

Quantum many-body phases in subwavelength brick wall lattice

D. Viarbitski[1], D. Burba[1] , G. Žlabys[2], G. Juzeliunas[1]

[1]*Institute of Theoretical Physics and Astronomy, Vilnius University, Sauletekio 3, Vilnius, Lithuania*
[2]*Okinawa Institute of Science and Technology Graduate University, Okinawa, Japan*

The study of quantum many-body systems has led to the discovery of numerous exotic quantum phases of matter, driven by the interplay between particle interactions, quantum fluctuations, and symmetry breaking. Among these, pair superfluids [1] and supersolids are particularly fascinating, as they represent different manifestations of quantum coherence and collective behavior in strongly correlated systems. In this paper, we propose a state-dependent lattice [2] for ultracold bosons based on a particular tripod atom-light coupling scheme [3]. We show that it manifests an extended Bose-Hubbard model and we explore the emergence of novel quantum phases, chief among them (pair) superfluids, supersolids, and Mott insulators.

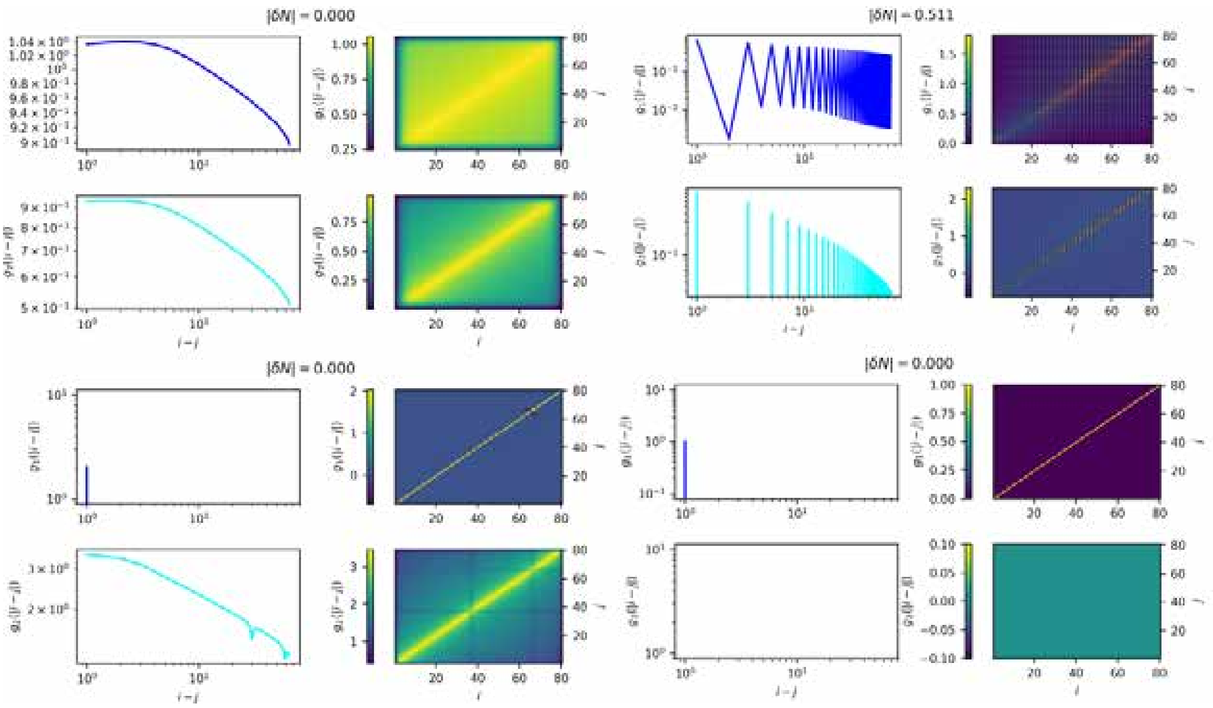


Figure 1: Bottom-right (MI): Quantities for following p-band parameters in canonical ensemble: J1 = J2 = 0, g0 = 1.0, gx = 0, gz = 0, G000 = 1.0, G011 = G001 = 0.5, Npart = Nlat , Nlat = 80, boson-dim= 6 Top-right (SS): Quantities for following p-band parameters in canonical ensemble: J1 = 0.1/ 10, J2 = 0.1, g0= 0.5, gx = 0.5, gz = 0.05, G000 = 1, G011 = G001 = 0.5, Npart = Nlat , Nlat = 80, boson-dim= 6. Top-left (SF): Quantities for following p-band parameters in canonical ensemble: J1 = J2 = 0, g0 = 1.0, gx = 0, gz = 1.0, G000 = 1, G011 = G001 = 0.5, Npart = Nlat , Nlat = 80, boson-dim= 6. Bottom-left (PSF): Quantities for following p-band parameters in canonical ensemble: J1 = J2 = 0, g0 = 0.1, gx = 1.0, gz = 0, G000 = 1, G011 = G001 = 0.5, Npart = 2Nlat , Nlat = 80, boson-dim= 6.

References

[1] X.-F. Zhou, Y.-S. Zhang, and G.-C. Guo, Phys. Rev. A **80**,013605 (2009).

[2] M. Eckholt and J. J. García-Ripoll, New Journal of Physics **11**, 093028 (2009).

[3] E. Gvozdiovas, P. Račkauskas, and G. Juzeliunas, SciPost Phys. **11**, 100 (2021).

Quantum metrology through spectral measurements in quantum optics

<u>A. Vivas-Viaña</u> and C. Sánchez Muñoz

Chalmers University of Technology and Institute of Fundamental Physics (IFF-CSIC)

Quantum optical systems can emit light with very complex spectral properties. For instance, the emergence of dressed states from coherently driven quantum emitters, hybridized excitonic states or hybrid light-matter states (polaritons) in cavity QED translate into rich fluorescence spectra with multiple peaks that reflect the complex structure of eigenstates. These spectra exhibit equally complex dependences with the parameters that govern the dynamics of the system [see Fig 1. (a)], and therefore offer the opportunity to improve the inference of unknown parameters by frequency-filtering the emitted signal.

Here, we explore this idea in quantum optical systems consisting of coherently driven quantum emitters in dissipative scenarios. Specifically, in Ref. [1], we focus on the estimation of the inter-emitter distance between two nonidentical interacting quantum emitters driven by a coherent field by measuring the fluorescence spectrum. We identify, by means of the Fisher information [2], that the two-photon resonance (i.e., when the laser frequency is at half of the energy of the doubly excited state) and the onset of the two-photon saturation regime (i.e., when the two-photon dressing effects begin to be resolved in the spectrum) are the most sensitive points for distance estimation [see Fig1. (b)].

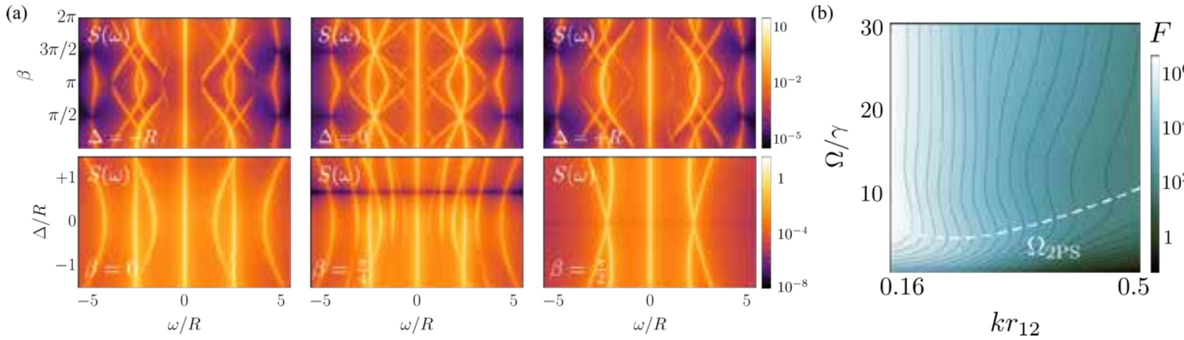


Fig. 1. (a) Resonance fluorescence spectrum in terms of the mixing angle $\beta=\mathrm{ArcTan}(J/\delta)$ (upper panels), and the qubit-laser detuning Δ (lower panels). (b) Fisher information in terms of the driving intensity Ω and the normalized inter-emitter distance kr_{12} at the two-photon resonance, $\Delta=0$.

It is known that hybridized light-matter systems, e.g., a strongly driven two-level system [3], give complex correlations in frequency space. Following this idea, we discuss the role of quantum correlations and quantify their impact on the precision by which unknown atomic parameters can be estimated, assessing the potential of frequency-resolved correlation measurements for the task of parameter estimation in driven-dissipative quantum optical systems.

[1] A. Vivas-Viaña and C. Sánchez Muñoz, Two-photon resonance fluorescence of two interacting nonidentical quantum emitters, Phys. Rev. Research 3, 033136 (2021).
[2] M. G. Paris, Quantum estimation for quantum technology, Int. J. Quantum Inf. 07, 125 (2009).
[3] C. Sánchez Muñoz, E. del Valle, C. Tejedor, and F. P. Laussy, Violation of classical inequalities by photon frequency filtering, Phys. Rev. A 90, 052111 (2014).

Quantifying non-Gaussianity with the SNAP-rank

Rui Wang[1], **Timo Hillmann**[1], **Ulysse Chabaud**[2], **Alessandro Ferraro**[3], **Giulia Ferrini**[1]

[1] *Department of Microtechnology and Nanoscience (MC2), Chalmers University of Technology, SE-412 96 Göteborg, Sweden*
[2] *DIENS, École Normale Supérieure, PSL University, CNRS, INRIA, 45 rue d'Ulm, Paris, 75005, France*
[3] *Quantum Technology Lab & Applied Quantum Mechanics Group, Dipartimento di Fisica "Aldo Pontremoli", Universit'a degli Studi di Milano, I-20133 Milano, Italia*

Quantum resource theories provide a powerful framework for characterizing and quantifying resources crucial to quantum information tasks. In this work, we introduce a resource measure for non-Gaussianity, a necessary element for achieving universal continuous-variable quantum computation (CVQC). In contrast to previous measures, such as the stellar rank which corresponds to the number of photon additions [1], our approach directly connects the resourcefulness of a state to the experimental procedure required for its generation in a circuit quantum electrodynamics architecture. Specifically, we focus on the selective number- dependent arbitrary phase (SNAP) gate, a non-linear operation forming a universal gate set for CVQC with the displacement gate [2]. We define the SNAP-rank as the minimum number of SNAP gates needed to prepare a given non-Gaussian state from a Gaussian reference state and prove that it provides a measure of non- Gaussianity. We use this framework to characterize states that can be prepared with few SNAP gates and Gaussian operations, and we compare the fidelity profiles for families of non-Gaussian states as a function of SNAP-rank and stellar rank. We show that using a few SNAP gates with Gaussian operations yields generated states with higher fidelity to target non-Gaussian states as compared to those produced by photon additions as quantified by the stellar rank.

References

[1] U. Chabaud, D. Markham, and F. Grosshans, Phys. Rev. Lett. **124**, 063605 (2020).

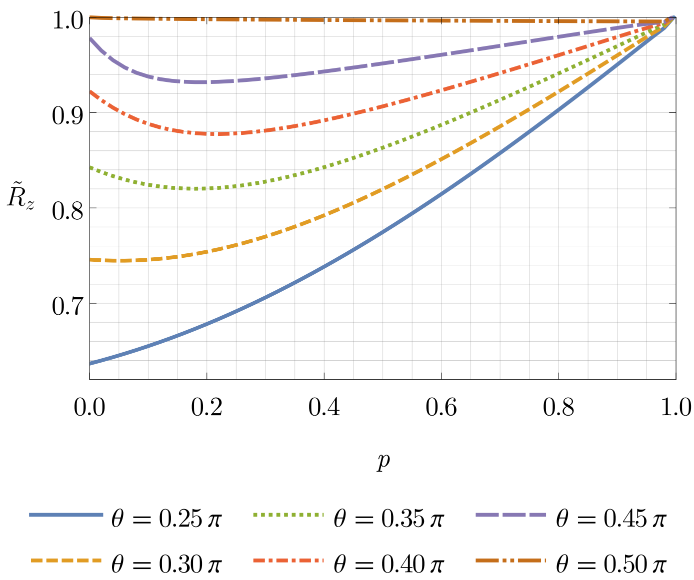
[2] R. W. Heeres, B. Vlastakis, E. Holland, S. Krastanov, V. V. Albert, L. Frunzio, L. Jiang, and R. J. Schoelkopf, Phys. Rev. Lett. **115**, 137002 (2013).

Recurrence in discrete-time quantum stochastic walks

M. Štefaňák[1], V. Potoček[1], İ. Yalçınkaya[1], A. Gábris[1,2], I. Jex[1]

[1]*Department of Physics, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Břehová 7, 115 19 Praha 1-Staré Město, Czech Republic*
[2]*Institute for Solid State Physics and Optics, HUN-REN Wigner Research Centre for Physics, 1525 P.O. Box 49, Hungary*

Interplay between quantum interference and classical randomness can enhance performance of various quantum information tasks. In the present paper we analyze recurrence phenomena in the discrete-time quantum stochastic walk on a line, which is a quantum stochastic process that interpolates between quantum and classical walk dynamics [**1**]. Surprisingly, we find that introducing classical randomness can reduce the recurrence probability — despite the fact that the classical random walk returns with certainty — and we identify the conditions under which this intriguing phenomenon occurs. Numerical evaluation of the first-return generating function allows us to investigate the asymptotics of the return probability as the step number approaches infinity. This provides strong evidence that the suppression of recurrence probability is not a transient effect but a robust feature of the underlying quantum-classical interplay in the asymptotic limit. Our results show that for certain tasks discrete-time quantum stochastic walks outperform both classical random walks and unitary quantum walks.



Recurrence probability for different values of the coin angle θ as a function of probability of taking a classical step p.

References

[1] M. Štefaňák, V. Potoček, İ. Yalçınkaya, A. Gábris, I. Jex, arXiv:2501.08674 [quant-ph](2025).

Topological Transport Properties of Height Modulated Subwavelength Barrier Lattices

G. Žlabys[1], W.-B. He[1], S. S. Nair[1], T. Busch[1], T. Ozawa[2]

[1] *Quantum Systems Unit, Okinawa Institute of Science and Technology Graduate University, Onna-son, Okinawa 904-0495, Japan*

[2] *Advanced Institute for Materials Research (WPI-AIMR), Tohoku University, Sendai 980-8577, Japan*

Ultracold atom gases trapped in optical potentials offer a clean and controllable platform to realize quantum models that are difficult to implement in condensed matter systems [1]. Recent theoretical [2] and experimental [3] developments allow to create periodic sub-wavelength potentials that overcome the diffraction limit imposed by the wavelength of the used laser beams. These potentials support the paradigmatic Kronig-Penney-type models which not only describe the behavior of electrons in a one-dimensional crystal but also have been shown to host topologically protected edge states [4]. Developing control strategies for such systems is of fundamental interest in quantum technologies that rely on robust states for computations [5].

In this work we analyze the topological properties of an advanced Kronig-Penney model. The emergent topological behavior is observed under translations and height modulation of the periodic potential in one dimension. The energy bands split into sub-bands displaying Hofstadter's butterfly-like structure under the change of the spatial modulation frequency. This leads to the redistribution of the topological invariants classifying the bands to a set of sub-bands indicating the same charge transport at lower filling. The transport is realized via adiabatic pumping and the spectral function is calculated showing the existence of topologically protected flat edge modes in the many-body case [6,7].

References

[1] P. Windpassinger et al., Rep. Prog. Phys. **76**, 086401 (2013).

[2] M. Lacki et al., Phys. Rev. Lett. **117**, 233001 (2016).

[3] Y. Wang et al., Phys. Rev. Lett. **120**, 083601 (2018).

[4] I. Reshodko et al., New J. Phys. **21**, 013010 (2019).

[5] C. P. Koch et al., EPJ Quantum Technol. **9**, 1 (2022).

[6] W.-B. He et al., Phys. Rev. A **111**, 013312 (2025).

[7] S. S. Nair et al., Phys. Rev. A **111**, 033313 (2025).

CONTENT