INVITED SPEAKERS

Mon 3rd July 2023

Bert Englert, *Centre for Quantum Technologies, NUS (Singapore)*

Uncertainty relations revisited

Abstract:
We routinely teach Heisenberg's uncertainty relation as well as Robertson's, and perhaps other, generalizations. It is common to regard the states that saturate the Robertson inequality as "minimum uncertainty states"; On closer inspection, it turns out that (i) the various inequalities are variants of one basic equation; (ii) the "minimum uncertainty states"; do not minimize uncertainty; (iii) the states that really minimize uncertainty obey a different equation than the ones that saturate the Robertson inequality.

Nicolas Cerf, *Université Libre de Bruxelles (Belgium)*

Anomalous photon bunching

Abstract:
The celebrated Hong–Ou–Mandel effect tells us that two photons impinging on a 50:50 beam splitter are always detected together in the same output mode. Since such a bunching results from a quantum interference effect, the complementarity principle dictates that it becomes less pronounced as soon as we are able to distinguish the photons and trace back which paths they have taken, for example, if the photons have orthogonal polarization. This interplay between photon bunching and distinguishability is commonly admitted to reflect a general rule: bunching must be maximum for fully indistinguishable photons and gradually decline when photons are made increasingly distinguishable. I will disprove this common assumption and exhibit an instance of anomalous photon bunching in an interferometric circuit involving seven photons.

Mark Hillery, *Hunter College, City University of New York (United States)*

Broadcasting a restricted set of states in a quantum network

Abstract:
Alice wants to send the same equatorial qubit state to Bob and Charlie, and she wants to use previously distributed entanglement to do it. In one version of this procedure she knows the state, so it is a multi-receiver version of remote state preparation. We propose a protocol that accomplishes this at a lower entanglement and classical communication cost than standard teleportation. In a second version, Alice receives a resource state that encodes the state to be broadcast, and uses it and the distributed entanglement to send the desired state to Bob and Charlie. In this case she does not have to know the state. We show how additional senders can be added to the network (more than one Alice) and discuss some applications of this procedure.

Reference

Mark Hillery, Janos A. Bergou, Tzu-Chieh Wei, Siddhartha Santra, and Vladimir Malinovsky, Broadcast of a restricted set of qubit and qutrit states, Phys. Rev. A 105, 042611 (2022).

Janos Bergou, *Hunter College, City University of New York (United States)*

Average concurrence and entanglement swapping

Abstract:
We discuss the role of average concurrence in entanglement swapping in quantum networks. First, we focus on qubit pure states, where there is a very simple rule governing the propagation of average concurrence in multiple swaps. We find a similarly simple rule for average concurrence when creating a Greenberger-Horne-Zeilinger state from three entangled pairs. We then look at examples of mixed qubit states and find that the relation for pure states gives an upper bound on what is possible with mixed states. We then move on to qudits, where we make use of the I-concurrence. Here the situation is not as simple as for qubits, but in some cases relatively straightforward results can be obtained. We also look at additional limitations arising from linear optical implementation, as in linear optical networks.

Peter Drummond, *Swinburne Universiy of Technology (Australia)*

Validating quantum computers: are they correct?

Abstract:
There are experimental claims of computational advantage with quantum computers. This raises theoretical questions of validation for the random-number generation tasks that are solved. How does one verify the output? Are the answers obtained even correct, and how can one test this in practice? Brute-force computational verification is not possible. No classical computer is large or fast enough for this, without taking billions of years. Computing the distributions is exponentially hard, not just from time and memory, but also due to finite precision numerical error propagation.

For Gaussian boson sampling, used in the largest computational advantage claims, we show that simulations in quantum phase-space can solve the verification problem by generating any diagnostic of the outputs that is measurable. This uses an FFT algorithm to obtain binned, computable statistics, with up to 16,000 qubits in large test cases. This is far larger than in any current experiment. The result is that recent experimental data from China and USA is significantly different from theory, with over 100 standard deviations of discrepancy for some measured statistics. Possible explanations are explored, but this is nontrivial, and we do not have a full explanation.

This does not disprove the computational advantage claims. These are very hard tasks, and phase-space methods do not directly generate the random numbers. However, the quantum network outputs do not currently survive the chi-squared tests normally employed to test validity of random numbers, as used in numerous cryptography applications. Another application of these methods is to show that faking the results is much harder than previously thought, since one can use a subset of exponentially many high-order binning methods to rule out classical fakes. We test this on some proposed classical fake algorithms, and show they can be ruled out.

Finally, we point out how similar techniques may in future be useful in testing other quantum network and computer designs. The principle is to use scalable methods that generate probabilities, rather than trying to use naive number-state algorithms on classical machines, which are now impractical.

Jasmin Meinecke, *LMU Munich (Germany)*

Quantum Simulations in Integrated Waveguide Arrays

Abstract:
Photons are a promising physical system to be used in emerging quantum technologies due to low decoherence properties and fast transmission times in optical circuits and channels. Integrated photonic waveguides, in particular, have been established as a versatile platform able to control path degree as well as polarization based photonic quantum states with high precision.

I will introduce integrated circuits as a tool for quantum simulations using quantum walk based models. Waveguide arrays are especially suitable to realize continuous-time quantum walks. The energy flow in such simulated quantum systems is of particular interest, since it provides information about the time evolution and dynamics of the system. By using weak measurement techniques to perform spatially resolving momentum measurements, we reconstruct energy flow lines corresponding to particle trajectories predicted by Bohmian mechanics, a non-local hidden variable theory. This allows to partially recover the classical intuition of particle trajectories that underlie classical random walks.

While quantum random walks are Markovian processes where the system under investigation is well separated from any environment interacting with it, the coupling between path as well as polarization degree of freedom provides a way to simulate open quantum systems and Non-Markovian processes in integrated structures. Using the trace distance between quantum states as a measure of information, we analyse different types of information transfer within open quantum systems. Extending the usual perspective which is focused on the system alone, we also investigate the presence of information in the environment. This analysis of the controlled interaction of quantum states provides a basis of fundamental investigations of quantum mechanics as well as implementations utilizing quantum effects for quantum technological applications.

Roberta Zambrini, *IFISC (UIB-CSIC) (Spain)*

Monitoring time series processing

Abstract:
Time-series processing is a major challenge in machine learning with enormous progress in the last years in tasks such as speech recognition and chaotic series prediction. A promising avenue for sequential data analysis is quantum machine learning, with computational models like quantum neural networks and reservoir computing. An open question is how to efficiently include quantum measurement in realistic protocols while retaining the needed processing memory and preserving the quantum advantage offered by large Hilbert spaces. In this work, we propose different measurement protocols and assess their efficiency in terms of resources, through theoretical predictions and numerical analysis. We show that it is possible to exploit the quantumness of the reservoir and to obtain ideal performance both for memory and forecasting tasks with two successful measurement protocols. One repeats part of the experiment after each projective measurement while the other employs weak measurements operating online at the trade-off where information can be extracted accurately and without hindering the needed memory, in spite of back-action effects. Our work establishes the conditions for efficient time-series processing paving the way to its implementation in different quantum technologies.

REFERENCE: npj Quantum Information (2023) 9:16; arXiv:2205.06809

Magdalena Stobinska, *University of Warsaw (Poland)*
Extremely robust topologically-protected edge states

Abstract:
In recent years, the study of topologically non-trivial structures in one-dimensional models has been dominated by the Su-Schrieffer-Heeger model due to its simplicity in design and its ability to support edge states with robustness to disorder, protected by chiral and inversion symmetry. We present a novel study on a zigzag quasi-one-dimensional model, which supports topologically protected edge states without relying on conventional symmetries. Our model utilises next-neighbour couplings to mediate edge states and demonstrate robustness to disorder. In order to understand the topological properties of this model, we introduce a novel way to demonstrate the bulk-boundary correspondence of the edge states and construct a topological invariant that returns quantized values. Our study sheds light on the possibility of constructing topological phases in new ways, even in the absence of conventional symmetries, and opens up new avenues for research in this field. In addition, we demonstrate possible realizations of these models on different platforms.

Tue 4th July 2023

Konrad Banaszek, *University of Warsaw (Poland)*
Towards quantum-limited operation of optical communication systems

Abstract:
Quantum statistical properties of electromagnetic radiation determine the ultimate capacity limits of optical communication links. With increasing sophistication of techniques available for optical signal processing and detection it is interesting to examine how these advances can bring the performance of optical communication systems closer to the quantum limits. This talk will review selected recent results in this area with a focus on photon-starved communication and optically amplified multispan links.

Alessandro Zavatta, *National Institute of Optics, CNR-INO (Italy)*
Quantum Communications with Squeezed States

Abstract:
Quantum secure direct communication (QSDC) is a recently developed practical solution that transmits secret messages between legitimate parties without setting up a cryptographic key. The QSDC protocols have been implemented on optical fibre and free-space channels, all in discrete-variable encoding that employs single-photon detectors. However, the implementation of continuous-variable QSDC approaches, in which the keys are encoded into the quadratures of quantised electromagnetic fields (e.g., coherent states) and detected via homodyne techniques, is preferred due to: its lower costs, excellent integrability with existing optical communication systems, easy implementation from state preparation to measurement, and fast experimental realisation. On the other hand, it has been proved that continuous-variable QSDC protocols using squeezed states show higher tolerance in purely lossy channels and enhanced robustness against highly noisy ones. Nevertheless, continuous-variable QSDC protocols employing coherent or squeezed quantum states still need to be implemented.

Here, we propose and realise a practical QSDC protocol (through the optical fibre quantum channel) based on coherent and squeezed state sources and homodyne detection. In addition to the secure proof-of-principle implementation of the continuous-variable QSDC protocol, we show the advantage of squeezed states over coherent states for achieving higher secrecy and robust, secure communications within lossy/noisy channels.

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Elisabetta Paladino, *Università di Catania (Italy)*

Adiabatic quantum operations in systems of ultrastrongly coupled matter and radiation

Abstract:
We consider systems of two or more qubits ultrastrongly coupled to a common resonator investigating ultrafast quantum operations. State transfer protocols based on quantum Rabi oscillations controlled by modulating the atoms-cavity couplings were studied previously proving to be inefficient even in ideal conditions, the main problem being the dynamical Casimir effect which determines uncorrectable irreversible leakage from the logic subspace. We propose to operate the resonator as a virtual quantum bus which suppresses uncorrectable errors and design a local control eliminating renormalization errors in the logic subspace. We prove analytically that the fidelity of many adiabatic operations is limited by population transfer, and show how to implement state transfer, swap operations and generation of bi- and multi-partite entanglement with very large fidelities at clock rates much larger than in the usual strong coupling regime. These figures are further improved by using optimal control theory and prove to be robust in the presence of noise. Our results suggest that ultrastrongly coupled structures provide promising building blocks for modular quantum computing.

Daniel Burgarth, *Friedrich-Alexander Universität (Germany)*

Taming the Rotating Wave Approximation

Abstract:
The Rotating Wave Approximation (RWA) is one of the oldest and most successful approximations in quantum mechanics. It is often used for describing weak interactions between matter and electromagnetic radiation. In the semi-classical case, where the radiation is treated classically, it was introduced by Rabi in 1938. For the full quantum description of light-matter interactions it was introduced by Jaynes and Cummings in 1963.
Despite its success, its presentation in the literature is often somewhat handwavy, which makes it hard to handle both for teaching purposes and for controlling the actual error that one gets by performing the RWA. Bounding the error is becoming increasingly important. Recent experimental advances in achieving strong light matter couplings and high photon numbers often reach regimes where the RWA is not great. At the same time, quantum technology creates growing demand for high-fidelity quantum devices, where even errors of a single percent might render a technology useless for error-corrected scalable quantum computation. I will give a gentle introduction to the history of the RWA and then report a conceptually simple way of explaining it. Finally, I will show how to tame it by providing non-perturbative error bounds, both for the semi-classical case and the full quantum case.

Virginia D'Auria, *Université Côte d’Azur (France)*

Quantum Photonics for applied quantum communication technologies

Abstract:
Quantum technologies exploting guided optics and integrated photonics represent a field in fully expansion due to the possibility of covering a wide panel of quantum light-based applications with miniaturized, reconfigurable and scalable architectures. In this talk, I will present our results on the development of telecom-compatible photonics solutions for long-range quantum communication as well as for the investigation of more fundamental quantum optical aspects. The generation and manipulation of quantum states of light will be discussed by presenting plug-n-play as well as integrated optics solutions relying on different technological platforms such as lithium niobate (LN) and silicon-nitride (SiN).

Marco Liscidini, *University of Pavia (Italy)*

Generation of high-dimensional states in photonic integrated platforms

Abstract:
We will discuss recent developments in the generation of high-dimensional quantum states using frequency-bin by leveraging the flexibility of light manipulation and dense optical integration in a nano-photonic platform. Our approach is based on the generation of nonclassical light by spontaneous four-wave mixing in photonic integrated devices. We show that frequency-bin entangled qudits can be constructed by direct, on-chip control of the interference of probability amplitudes of photon pairs coherently generated by different nanophotonic sources. States are built “piece-by-piece" in a programmable and scalable way, by selecting the relative phase of each source. This approach is implemented in a silicon device, with the generated states validated by quantum state tomography for two-qutrit and two-ququart cases.

Alessia Allevi, *University of Insubria (Italy)*

Mesoscopic states of light for the implementation of novel underwater quantum communication protocols

Abstract:
Exploiting quantum resources can improve the security of information transmission between two parties. Until now, Quantum Communication protocols have been implemented at the single-photon level by means of entangled states of light. Unlike in this domain, where the presence of losses can reduce the transmission rate of information, in the mesoscopic intensity regime the optical pulses contain sizeable numbers of photons, thus resulting more robust against any kind of external degradation. In some works of ours, we have demonstrated that the transmission of one arm of a twin-beam (TWB) state through a lossy and noisy channel does not prevent the observation of nonclassical correlations between the two parties by using the noise reduction factor as a criterion for non-classicality.
More recently, we have implemented a more realistic scenario, in which a portion of TWB is sent through water-filled tubes, while the other one undergoes free-space propagation. We investigate the role played by the length of the tubes, the number of optical elements, and the divergence of the beams through the different media. We demonstrate that, by properly acting on the light beams, we can still observe nonclassical correlations at moderate distances. The experimental implementations involve two classes of commercial photon-number-resolving detectors: hybrid photodetectors and Silicon Photomultipliers.
Based on these successful results, we also demonstrate that a novel communication protocol based on the experimental quantification of non-classicality of mesoscopic twin-beam states can be used to transmit binary signals encoded in two single-mode pseudothermal states with different mean values through a water channel. The experimental results are in perfect agreement with the developed theoretical model, and the feasibility of the protocol is also studied as a function of the data samples corresponding to each one of the two signals. The good quality of the results encourages a more realistic implementation of the protocol as well as further investigations on other kinds of light states that can be used to encode the binary signals.

Alberto Porzio, *INFN Napoli, Università di Cassino e del Lazio Meridionale (Italy)*

GINGERINO a quantum gyroscope

Abstract:
Absolute angular rotation rate measurements with sensitivity better than prad/sec would be beneficial for fundamental science investigations. On this regard, large frame Earth based ring laser gyroscopes are top instrumentation as far as bandwidth, long term operation and sensitivity are concerned.

GINGERINO, the active ring laser prototype of the INFN GINGER collaboration, has shown an unprecedented sensitivity close to 2×10^{-15} rad/sec for $\sim 2\times 10^{5}$ s of integration time. This sensitivity is more than a factor 10 better than the shot--noise as defined by actually accounted theoretical prediction for ring lasers.

The usually adopted theoretical model relies on the strong hypothesis that the two counter propagating beams are completely independent so that their field variables are uncorrelated. In this context, the shot-noise for a ring laser is the sum of the shot-noise accounted for the two single beams.

In this contribution we will present the experimental determination of the GINGERINO noise limit in its present configuration and discuss possible novel approach for elaborating an amended theoretical model that accounts for the interaction of the two beams at a quantum level.

Wed 5th July 2023

Marco Genovese, *INRIM (Italy)*

Single photon pair measurement of the Bell parameter

Abstract:
Bell inequalities are one of the cornerstones of quantum foundations and fundamental tools for quantum technologies.

Recently, the scientific community worldwide has put a lot of effort towards them, which culminated with loophole-free experiments. Nonetheless, none of the experimental tests so far was able to extract information on the whole inequality from each entangled pair, since the wave function collapse forbids performing, on the same quantum state, all the measurements needed for estimating the entire Bell parameter.

We present here the first single-pair Bell inequality test able to obtain a Bell parameter value for every entangled pair detected [1]. This is made possible by exploiting sequential weak measurements, allowing to perform non-commuting measurements in sequence on the same state, on each entangled particle. Such a feature not only grants unprecedented measurement capability, but also removes the need to choose between different measurement bases, intrinsically eliminating the freedom-of-choice loophole.

We also demonstrate how, after the Bell parameter measurement, the pair under test still presents a noteworthy amount of entanglement, providing evidence of the absence of the wave function collapse and allowing us to exploit of this quantum resource for further protocols.

[1] Salvatore Virzì, Enrico Rebufello, Francesco Atzori, Alessio Avella, Fabrizio Piacentini, Rudi Lussana, Iris Cusini, Francesca Madonini, Federica Villa, Marco Gramegna, Eliahu Cohen, Ivo Pietro Degiovanni, Marco Genovese arXiv:2303.04787

Philippe Grangier, *CNRS / Institut d'Optique (France)*

Contextual inferences, nonlocality, and the incompleteness of quantum mechanics

Abstract:
It is known that "quantum non locality" leading to the violation of Bell's inequality and more generally of classical local realism, can be attributed to the conjunction of two properties, that we call here elementary locality and predictive completeness. Taking this point of view, we show again that quantum mechanics violates predictive completeness, allowing to make contextual inferences, which can in turn explain why quantum non locality does not contradict relativistic causality. But if the usual quantum state ψ is predictively incomplete, how to complete it? We give here a set of new arguments to show that ψ should be completed indeed, not by looking for any "hidden variables", but rather by specifying the measurement context, which is required to define actual probabilities over a set of mutually exclusive physical events. We will discuss mathematical implications of this claim towards operator algebras.

Margaret Reid, *Swinburne University of Technology (Australia)*

Macroscopic realism, Bell inequalities and hidden causal loops: a model for measurement based on the Q function

Abstract:
We examine realism and the measurement problem in quantum mechanics [1].

We first demonstrate violations of macrorealism, and of macroscopic Bell inequalities, where measurements distinguish between two macroscopically-distinct coherent states. More generally, we map from microscopic to macroscopic paradoxes, where the polarising beam splitters that enable unitary rotations to determine measurement settings are replaced by unitary interactions arising from nonlinear Hamiltonians. This leads to two definitions of macroscopic realism: weak macroscopic realism (wMR) and deterministic macroscopic realism (dMR). We find failure of dMR, but consistency with wMR [2].
This motivates weak local realism (wLR) which posits a real property for the system at the time after the interaction that determines the measurement setting. The real property gives a predetermined value for the outcome of the measurement. This value is not affected by spacelike-separated interactions. Consider the Einstein-Podolsky-Rosen (EPR) premise: if one can predict with certainty the outcome of a measurement of a physical quantity for system A, without disturbing that system, then there exists an element of reality for that quantity. Weak local realism posits the following modification: if one can predict the value for A by measurement on a spacelike-separated system B, then the element of reality at A exists, provided the unitary interactions that fix the measurement setting at B have occurred. We show that EPR, Bell, delayed-choice, and Wigner's-friend paradoxes are consistent with wLR [2].
We examine an Objective-Quantum-Field-Theory model for quantum measurement, based on quantum phase-space solutions that lead to Q function trajectories propagating forward and backward in time [1]. This implies a retrocausality leading to a "hidden" causal loop-like structure, but which remains consistent with wMR (which is macroscopically nonretrocausal). This elucidates the measurement problem.
For a cat-state, wMR implies an incompleteness of (standard) quantum mechanics: If wMR is valid, then the system is in one or other of two macroscopically distinct states; but these 'states' cannot be quantum states. They can however be explained by quantum theory, using the trajectories.
We demonstrate trajectories consistent with wLR and wMR for the EPR paradox and continuous-variable Bell violations. This explains Schroedinger's question about simultaneous measurements of x and p [3]. We discuss the creation of entanglement.

[1] P.Drummond and M.Reid, Phys. Rev. Research 2, 033266 (2020). Arxiv:2205.06070; 2303.02373 and references therein
[2] M.Thenabadu and M.Reid, Phys. Rev. A 105, 052207 (2022). J.Fulton et al, arXiv:2208.01225; R.Rushin et al, arXiv:2211.02877
[3] E.Schroedinger, Die Naturwissenschaften 23, 844 (1935)

Mauro Paternostro, *Queen's University Belfast (United Kingdom)*
Quantum neuromorphic approach for efficient sensing of gravity-induced entanglement

Abstract:
The detection of entanglement provides a definitive proof of quantumness. Its ascertainment might be challenging for hot or macroscopic objects, where entanglement is typically weak, but nevertheless present. I will discuss a platform for measuring entanglement by connecting the objects of interest to an uncontrolled quantum network, whose emission (readout) is trained to learn and sense the entanglement of the former. First, I will demonstrate the platform and its features with generic quantum systems. As the network effectively learns to recognise quantum states, it is possible to sense the amount of entanglement after training with only non-entangled states. Furthermore, by taking into account measurement errors, I demonstrate entanglement sensing with precision that scales beyond the standard quantum limit and outperforms measurements performed directly on the objects. Finally, I will utilise such platform for sensing gravity-induced entanglement between two masses and predict an improvement of two orders of magnitude in the precision of entanglement estimation compared to existing techniques.

Howard Wiseman, *Griffith University (Australia)*
Can super-radiant lasers achieve the Heisenberg limit for laser coherence?

Abstract:
For more than 60 years, the Schawlow-Townes limit [1] was thought to limit the laser coherence $\mathfrak{C}$ — the number of photons emitted from the laser into the beam in one coherence time — to a scaling O(μ^2), where μ is the mean number of optical-frequency excitations stored inside the laser. However, recently it was shown [2,3] that this is just a standard quantum limit (SQL). The Heisenberg limit — an achievable ultimate limit set by quantum mechanics for the task of producing a beam with the standard properties of a laser beam — is $\mathfrak{C}$ = O(μ^4), a quadratic enhancement [2,3]. So far, proposals to demonstrate beyond-SQL scaling of $\mathfrak{C}$ have been limited to circuit QED, at microwave frequencies (i.e. a maser) [2,4]. Here we present the first optical-frequency laser platform that can surpass the Schawlow-Townes scaling: a super-radiant laser in the bad-cavity limit with feedback-controlled collective pumping. We show that the coherence can exhibit a scaling as large as $\mathfrak{C} \sim \mu$^8/3, where here $\mu \approx$ N/2, where N is the number of super-radiant atoms. Using atoms with an ultranarrow clock transition (mHz), we predict that a laser linewidth (the reciprocal of the coherence time) below 100 µHz could be attainable. This is more than an order of magnitude below standard super-radiant lasers, where the linewidth is limited to the transition width.

[1] A. L. Schawlow and C. H. Townes, "Infrared and optical masers", Phys. Rev. 112, 1940–1949 (1958).
[2] Travis J. Baker, Seyed N. Saadatmand, Dominic W. Berry, and Howard M. Wiseman, "The Heisenberg limit for laser coherence", Nature Physics 17, 179–183 (2021).
[3] L. A. Ostrowski, T. J. Baker, S. N. Saadatmand, and H. M. Wiseman, "No Tradeoff between Coherence and Sub-Poissonianity for Heisenberg-Limited Lasers", Phys. Rev. Lett. to appear (2023).
[4] C. Liu et al., "Proposal for a continuous wave laser with linewidth well below the standard quantum limit", Nature Communications 12, 10.1038/s41467-021-25879-8 (2021).

Morgan Mitchell, *ICFO (Spain)*

Number-unconstrained quantum sensing and quantum limits in field sensing

Abstract:
Quantum sensing is one of the “pillars” of quantum technology, and is frequently framed using concepts from quantum computing, another pillar. For example, interferometric measurement is often described assuming a fixed number N of available particles, in the same way that a quantum computer might be assumed to have an N-bit register. This assumption, in a linear interferometer, leads to well-known phase estimation limits $\delta\phi \geq 1/\sqrt{N}$ with non-entangled particles and $\delta\phi \geq 1/N$ with entangled particles. The N-scaling of these results is often given importance in the theoretical literature, as if changing the scaling per se were a desideratum, as is the case in computational complexity theory. The bad fit of this approach to actual practice is evident in the fact that, while many experiments have demonstrated sensitivity beyond the SQL, a scaling other than $\delta\phi \propto 1/\sqrt{N}$ is almost never observed in experiment. In this talk, I would like to suggest that quantum sensing would be better served by giving particle number a quite different role, similar to the role it has in quantum many-body physics (or in quantum simulation, another pillar). I will first argue that a number-unconstrained quantum sensing picture is natural for many (possibly most) quantum-limited sensors. I will then describe how number-independent quantum limits emerge from optimization of particle number in interferometric measurement with realistic inter-particle interactions. In the case of magnetic sensing, this leads to a remarkable “energy resolution limit” that has been shown in theory for multiple advanced magnetometer technologies, and empirically holds for all the demonstrated sensors to date. Finally, I will describe experimental quantum sensitivity enhancement of number-optimized measurements using non-classical states.

S. P. Alvarez, P. Gomez, S. Coop, R. Zamora-Zamora, C. Mazzinghi, and M. W. Mitchell. Single-domain Bose condensate magnetometer achieves energy resolution per bandwidth below hbar. Proceedings of the National Academy of Sciences, 119, e2115339119 (2022)

C. Troullinou, R. Jiménez-Martínez, J. Kong, V. G. Lucivero, and M. W. Mitchell. Squeezed-light enhancement and backaction evasion in a high sensitivity optically pumped magnetometer. Phys. Rev. Lett., 127, 193601 (2021)

M. W. Mitchell and S. Palacios Alvarez. Colloquium: Quantum limits to the energy resolution of magnetic field sensors. Rev. Mod. Phys., 92, 021001 (2020)

M. W. Mitchell. Number-unconstrained quantum sensing. Quantum Science and Technology, 2, 044005 (2017)

David Vitali, *University of Camerino (Italy)*

Quantum receivers for microwave quantum illumination

Abstract:
Entanglement is vulnerable to degradation in a noisy sensing scenario, but the quantum illumination protocol has demonstrated that its advantage can survive. However, designing a measurement system that realizes this advantage is challenging since the information is hidden in the weak correlation embedded in the noise at the receiver side. Recent progress with a correlation-to-displacement conversion module provides a route towards an optimal protocol for practical microwave quantum illumination. In this work, we consider the effect of experimental imperfections that are ubiquitous in microwave systems.
To mitigate loss, we propose amplification of the return signals. In the case of ideal amplification, the entire six-decibel error-exponent advantage in target detection error can be maintained. However, in the case of noisy amplification, this advantage is reduced to three-decibel. We analyze the quantum advantage under different scenarios with a Kennedy receiver in the final measurement. In the ideal case, the performance still achieves the optimal one over a fairly large range with only on-off detection. Empowered by photon number resolving detectors, the performance is further improved and also analyzed in terms of receiver operating characteristic curves. Our findings pave the way for the development of practical microwave quantum illumination systems.

Thu 6th July 2023

Giulia Ferrini, *Chalmers University of Technology (Sweden)*

The vacuum provides quantum advantage to otherwise simulatable architectures

Abstract:
Identifying the physical resources underlying quantum advantage — i.e., yielding the ability of quantum computers to solve computational problems faster than classical computers — is of crucial importance for the design of meaningful architectures for quantum computation. Often, the resource depends on the model. In this work we provide a specific example of a continuous-variable (CV) quantum computing architecture where the resource promoting a classically efficiently simulatable to a universal one is the vacuum. The latter state is widely regarded as the simplest quantum state of a bosonic field, and in particular it is a Gaussian state. The architecture considered is based on Gottesman-Kitaev-Preskill (GKP) states, Gaussian operations and measurement of the quadratures of the bosonic field. First we prove that this class of circuits is classically efficiently simulatable for most Gaussian operations. Then, we leverage on recent results where the same architecture combined with the vacuum (or a thermal) state was shown to be universal for quantum computation, to conclude that the vacuum provides quantum advantage. Finally, we present a sufficient condition for determining the resourcefulness of other CV states (beyond the vacuum) in the context of promoting these simulatable circuits to universality. This method is based on decomposing the CV state as a qubit state, and consider maps that are physically implementable by means of resourceless circuits.

Natalia Korolkova, *University of St. Andrews (United Kingdom)*

Coherent Diffusive Photonics: Quantum engineering by nonlocal loss

Abstract:
Coherent Diffusive Photonics (CDP) [1] emerges from a combination of collective behaviour through coupling to the common environment and coherence supported through an engineered nonlinear loss mechanism. The combination of these opposites allows for coherent light control that can be exploited in simulation of complex quantum dynamics in open systems or to design practical deterministic integrated sources of non-classical light [2,3] with previously inaccessible operational regimes.
The key element here is engineered nonlocal loss, where we also leverage nonlinear dynamics. Engineered loss has already turned into a powerful and intensively researched tool for quantum state manipulation. However, it is considerably harder to engineer losses in photonic circuits. In this work we exploit the effects of nonlocal and nonlinear loss, in the first-place nonlinear coherent loss, and devise photonic circuits with unusual and attractive features. The core element is a system of bosonic modes coupled pairwise to a common reservoir. Crucially, the dissipation into these reservoirs is nonlinear in field operators. That is, in the master equation, the Lindblad operator is in general a nonlinear function of bosonic creation and annihilation operators and the exact form of this function is a handle to unlock a particular type of quantum dynamics in this open system and to attain a particular quantum state at the output.
In this talk, I will present the theoretical foundations for Coherent Diffusive Photonics and discuss several schemes for integrated quantum sources and optical routing devices based on CDP and will outline the ideas for topological effects in the system.
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] 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).
[3] 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).

Mattia Walschaers, *Laboratoire Kastler Brossel, CNRS (France)*

Non-Gaussian resources for photonic quantum technologies

Abstract:
Quantum technologies promise dramatic improvements over classical devices. For a range of applications, optics is a promising platform to implements such quantum technologies. We have a long history of manipulating light, and it is reasonably robust to detrimental decoherence effects. This allows, for example, the creation of entangled states with thousands or even millions of modes. However, our enthusiasm must be tempered, since quantum technologies often require non-Gaussian states of light to unlock their full potential.
The non-Gaussian resources that enable us to achieve a computational or metrological advantage are challenging to pinpoint. Often it is not a single resource but the subtle interplay of many that can be held responsible for these potential advantages. In this talk, we will first focus on computational aspects and show that every bosonic quantum computation can be recast into a continuous-variable sampling computation where all computational resources are contained in the input state [1]. Using this reduction, we derive a general classical algorithm for the strong simulation of bosonic computations, whose complexity scales with the non-Gaussian stellar rank of both the input state and the measurement setup. We further study the conditions for an efficient classical simulation of the associated continuous-variable sampling computations and identify an operational notion of non-Gaussian entanglement based on the lack of passive separability as a requirement. It turns out that this entanglement also serves as a resource for a metrological quantum advantage. We use this observation to propose new protocols for the detection of non-Gaussian entanglement in experiments [2].

[1] U. Chabaud and MW, Resources for Bosonic Quantum Computational Advantage, Phys. Rev. Lett. 130, 090602 (2023)
[2] D. Barral, M. Isoard, G. Sorelli, M. Gessner, N. Treps, MW, Metrological detection of purely-non-Gaussian entanglement, arXiv:2301.03909

Radim Filip, *Palacký University (Czech Republic)*
Quantum Non-Gaussian Light and Mechanics

Abstract:
The talk will report recent theoretical and experimental achievements opening the door to highly non-Gaussian quantum states of photons and phonons. This territory is challenging for investigation, both theoretically and experimentally. We will present recent achievements, mainly the experimental tests of climbing the hierarchy of quantum non-Gaussian phononic and photonic states suitable for applications. Particular focus will be on new nonclassical and quantum non-Gaussian coherences and their experimental verification. The talk will conclude with other related results and the following challenges in theory and experiments with atoms, mechanical oscillators and superconducting circuits to stimulate discussion and further development of this advancing and prospective field.

Lorenzo Maccone, *University of Pavia (Italy)*
Quantum metrology of noisy spreading channels

Abstract:
We provide the optimal measurement strategy for a class of noisy channels that reduce to the identity channel for a specific value of a parameter (spreading channels). We provide an example that is physically relevant: the estimation of the absolute value of the displacement in the presence of phase randomizing noise. Surprisingly, this noise does not affect the effectiveness of the optimal measurement. We show that, for small displacement, a squeezed vacuum probe field is optimal among strategies with same average energy. A squeezer followed by photodetection is the optimal detection strategy that attains the quantum Fisher information, whereas the customarily used homodyne detection becomes useless in the limit of small displacements, due to the same effect that gives Rayleigh's curse in optical superresolution. There is a quantum advantage: a squeezed or a Fock state with N average photons allow to asymptotically estimate the parameter with a sqrt(N) better precision than classical states with same energy.

This talk is based on the paper [W. Gorecki, A. Riccardi, L. Maccone, Quantum metrology of noisy spreading channels, Phys. Rev. Lett. 129, 240503 (2022)], from which the above abstract is taken.

Fri 7th July 2023

Paolo Villoresi, *Università di Padova (Italy)*

Advancements on Quantum Communications in Space

Abstract:
Developments of Space Quantum Communications require dedicated quantum devices suitable for the harsh environmental conditions and with enhanced performances.
Suitable solutions for advanced payload are presented, including record low noise qubit generators and synchronization methods.
A recent review of quantum optical experiment to be performance in space will also be briefly presented.

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[2] C. Agnesi et al., “Simple quantum key distribution with qubit-based synchronization and a self-compensating polarization encoder,” Optica, vol. 7, no. 4, p. 284, Apr. 2020.
[3] D. Dequal et al., “100 kHz satellite laser ranging demonstration at Matera Laser Ranging Observatory,” J. Geod., vol. 95, no. 2, p. 26, Feb. 2021.
[4] M. Avesani, C. Agnesi, A. Stanco, G. Vallone, and P. Villoresi, “Stable, low-error, and calibration-free polarization encoder for free-space quantum communication,” Opt. Lett., vol. 45, no. 17, p. 4706, Sep. 2020.
[5] M. Avesani et al., “Resource-effective quantum key distribution: a field trial in Padua city center,” Opt. Lett., vol. 46, no. 12, p. 2848, Jun. 2021.
[6] M. Mohageg et al., “The deep space quantum link: prospective fundamental physics experiments using long-baseline quantum optics,” EPJ Quantum Technol., vol. 9, no. 1, p. 25, Dec. 2022.

Fabio Sciarrino, *Sapienza Università di Roma (Italy)*

Hybrid Photonics Platform for Quantum Information Processing

Abstract:
The development of optical quantum technologies allows for quantum-enhanced metrology, secure quantum communication, and quantum computing and simulation in highly increased dimensions. Maturing quantum photonics requires efficient generation and detection of single photons, as well as their scalable manipulation. We merge highly efficient multi-photon sources and integrated waveguide components. In particular, we interface these scalable platforms, demonstrating high-rate multi-photon interference with a quantum dot based multi-photon source and a reconfigurable photonic chip on glass. We will then review applications of this platform to quantum computing and quantum metrology.

Christiane Koch, *Freie Universität Berlin (Germany)*
Minimizing resources for quantum devices with control theory

Abstract:
Quantum technologies are all about controlling quantum systems. Control is the prerequisite to exploit the two essential elements of quantum physics, non-locality and coherence, for practical applications. This currently faces two major challenges --- to preserve the relevant non-classical features at the level of device operation and to scale the devices up in size. Control theory provides tools for tackling both challenges. On the one hand, controllability analysis aims at answering the question which control targets, states or operations, are accessible. On the other hand, control theory provides methods to derive the actual control fields that implement the desired dynamics. I will discuss how to leverage control theory to minimize resources for quantum devices and thus ease requirements towards scaling up their size. In particular, I will show how controllability analysis allows us to identify the minimum number of local controls required to implement universal quantum computing in an array of coupled qubits. Moreover, I will provide examples for the control of open quantum systems where the environment leads to decoherence but also opens new prospects for control. I will discuss examples for both strategies, with practical applications in Rydberg atoms, trapped ions, and superconducting circuits.

Giovanna Morigi, *Saarland University (Germany)*
Quantum dynamics of selforganization in many-body cavity quantum electrodynamics

Abstract:
Ensembles of atoms strongly coupled with the electric field of an optical cavity offer a formidable laboratory for studying the out-of-equilibrium dynamics of long-range systems in the quantum regime. In this work, we derive by means of the formalism developed in Ref. [1] a quantum master equation describing the dynamics of atoms which interact with a multimode high-finesse cavity. We then analyse the predictions in several relevant limits, namely semi-classical, mean-field, and beyond mean-field. Our theory reproduces the results of the experiment of Ref. [2] and provides a powerful tool for singling out the individual contributions to the onset of metastability in quantum globally-interacting systems.

[1] S. B. Jäger, T. Schmit, G. Morigi, M. J. Holland, and R. Betzholz, Phys. Rev. Lett. 129, 063601 (2022).
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Abolfalz Bayat, *University of Electronic Science and Technology of China (China)*
Near-term quantum simulators: from qubits to fermions

Abstract:
Quantum simulators are rapidly emerging in various physical platforms, from cold atoms and ions to superconducting devices. However, near-term quantum simulators suffer from various imperfections in their initialization, manipulation and readout. Indeed, achieving practical quantum advantage with near-term quantum simulators, beyond sampling, is hotly pursued in both theory and experiments. Variational quantum algorithms are the most promising approach to achieve such advantage. In these algorithms the complexity is divided between a quantum simulator and a classical optimizer, paving the way for a shallow quantum circuit to achieve quantum advantage. In this work, we explore different ways for exploiting symmetries for saving both quantum and classical resources for simulating several eigenstates of given Hamiltonians. The results have been experimentally realized in which full spectroscopy of a four- qubit system and partial spectroscopy of an eight-qubit system have been achieved. In addition, we investigate the resource consumption of fermionic quantum simulators in comparison to the conventional qubit-based quantum computers for emulating fermionic systems. We can quantitatively show that fermionic quantum simulators outperform their qubit counterpart for simulating fermionic systems and quantum chemistry problems. The advantage becomes even more pronounced as spin degrees of freedom are included, interaction between fermions increases or the dimension of the system is extended to 2D.

Jonatan Bohr-Brask, *Technical University of Denmark (Denmark)*

Bosonic autonomous entanglement engines with weak bath coupling are impossible

Abstract:
Entanglement is a fundamental feature of quantum physics and a key resource for quantum communication, computing and sensing. Entangled states are fragile and maintaining coherence is a central challenge in quantum information processing. Nevertheless, entanglement can be generated and stabilised through dissipative processes. In fact, entanglement has been shown to exist in the steady state of certain interacting quantum systems subject solely to incoherent coupling to thermal baths. This has been demonstrated in a range of bi- and multipartite settings using systems of finite dimension. Here we focus on the steady state of infinite-dimensional bosonic systems. Specifically, we consider any set of bosonic modes undergoing excitation-number-preserving interactions of arbitrary strength and divided between an arbitrary number of parties that each couple weakly to thermal baths at different temperatures. We show that the steady state is always separable.

Luca Innocenti, *Universita degli Studi di Palermo (Italy)*

Shadow tomography on general measurements frames

Abstract:
We provide a new perspective on shadow tomography by demonstrating its deep connections with the general theory of measurement frames. By showing that the formalism of measurement frames offers a natural framework for shadow tomography -- in which ``classical shadows'' correspond to unbiased estimators derived from a suitable dual frame associated with the given measurement -- we highlight the intrinsic connection between standard state tomography and shadow tomography. Such perspective allows us to examine the interplay between measurements, reconstructed observables, and the estimators used to process measurement outcomes, while paving the way to assess the influence of the input state and the dimension of the underlying space on estimation errors. Our approach generalizes the method described in [H.Y. Huang et al, Nat. Phys. 16, 1050 (2020)], whose results are recovered in the special case of covariant measurement frames. As an application, we demonstrate that a sought-after target of shadow tomography can be achieved for the entire class of tight rank-1 measurement frames -- namely, that it is possible to accurately estimate a finite set of generic rank-1 bounded observables while avoiding the growth of the number of the required samples with the state dimension.

Special session on EXPERIMENTAL QUANTUM METROLOGY
(supported by the *European Metrology Network for Quantum Technologies)*
Thu 6th July 2023

Alice Meda, *INRIM (Italy)*
Phase stabilization for Twin-field QKD in a real-world network

Abstract:
Quantum key distribution (QKD) is a quantum communication technology that allows the sharing of secret cryptographic keys between two distant users (Alice and Bob), whose intrinsic security is guaranteed by fundamental principles of quantum physics. Several QKD networks are under deployment worldwide and one of the main remaining challenges for this technology is the integration of different QKD solutions in already deployed telecommunication fiber networks, in particular in long haul segments.
An innovative approach to cover long distances is the Twin-field QKD (TF-QKD) protocol; TF-QKD presents a weaker dependence on channel losses, doubling the communication distance with respect to the conventional prepare-and-measure solutions. TF-QKD requires that the optical pulses are phase-coherent in Alice and Bob and preserve coherence throughout the path to a central node, Charlie. Although optical coherence of the laser sources used for the protocol can be achieved by phase-locking the QKD lasers in Alice and Bob to a common reference laser transmitted through a service channel, there still remains uncorrelated phase changes, introduced by length and refractive index fluctuations of the deployed optical fibers that compromise the stability of the interference measurement.
Here we present a solution to the phase stabilization problem, derived from atomic clocks comparison technology, that clearly demonstrates advantages in performances of real word TF- QKD. We designed and developed an apparatus suitable for TF-QKD where the phase fluctuations of both the lasers and of the connecting fibers are actively cancelled. We tested our solution in a real-world network where the distance between Alice and Bob is 206 km and the net losses are as high as 65 dB. We also analyzed in details the theoretical behavior of the key rate with respect to different parameters (phase noise, signal to noise ratio..) and studied possible trade-offs with different TF-QKD solutions.

Thierry Debuisschert, *Thales Research and Technology (France)*
TBA

Abstract:
TBA

Paolo Traina, *INRIM (Italy)*
Probing local temperature variations in neurons via Nanodiamond sensors

Abstract:
Temperature is one of the most relevant parameters for the regulation of intracellular processes. Measuring localized subcellular temperature gradients is fundamental for a deeper understanding of cell function, such as the genesis of action potentials, and cell metabolism.
In this work I will review our latest progresses in NV-based thermometry ultimately leading to the first localized temperature increase detection in a firing neuronal network with precision under 0.1 K.
By exploiting ODMR techniques, temperature variations in cultured hippocampal neurons at the single-cell scale using NV color centers in nanodiamonds are probed. Our data show that, in the spontaneously firing network, 1K local temperature increases can be detected after 1 mM picrotoxin administration, a selective blocker of the inhibitory GabaA receptors. Picrotoxin-induced temperature increases are associated to a

significant potentiation of the firing rate, whereas ODMR stimulation protocols do not affect cell viability and functionality. Thus, for the first time, it is possible to unravel the firing activity of the network from the observed temperature increases.
In perspective, this techniques will provide an extremely promising mean of indirect detection of the action potential and study of temperature variations in proximity of specific cell regions by functionalizing nanodiamonds in order to target specific cell components (e.g. ion channels, mitochondrions, ER).

Paolo Olivero, *University of Torino (Italy)*

Fabrication and characterization of MgV optical centers in diamond

Abstract:
Diamond is a promising platform for emerging quantum technologies, as it hosts optically active defects with appealing properties for the solid-state implementation of room temperature quantum information processing devices. The quest for single-photon emitters which can be consistently fabricated by ion implantation and display desirable opto-physical properties (high emission rate, narrow linewidth, microwave or optically-addressable spin states) is crucial to the development of quantum sensors and quantum repeaters. In this work we report on the systematic photoluminescence characterization of a recently discovered class of point defects based on Mg impurities in diamond. We perform a characterization of the emitters through single-photon photoluminescence (PL) confocal microscopy of high-purity CVD diamond samples implanted with 100 keV Mg subsequently thermally annealed. A PL investigation both at ensemble and single-photon emitter level of their emission properties performed at different excitation wavelengths in the 405-535 nm range and at different temperatures in the range 4–300 K reveals the relevant properties of the Mg-related class of emitters. Moreover, the structural properties of these point defects is experimentally determined by means of the emission channeling technique using 27Mg-implanted diamond. This analysis offers an insight in the atomic configuration of the emitting defect in terms of lattice site position and its efficiency of formation. These results are discussed with respect to recently proposed theoretical predictions available in the scientific literature.

Marco López, *Physikalisch-Technische Bundesanstalt (Germany)*

Study on the detection efficiency of InGaAs single-photon avalanche diodes as a function of mean photon number and repetition rate

Abstract:
Single-photon detectors are essential building blocks in many photonic quantum technologies. For applications such as quantum communication, the precise determination of the detector response to the incoming photons is crucial to avoid security breaches. Consequently, validated measurement methods and measurement procedures are required to achieve a reliable characterization of the detector response. Here we present a detailed study on the accurate determination of the detection efficiency of commercial single-photon detectors based on InGaAs avalanche diodes, operated in free-running mode, for various mean photon numbers and at high laser pulse repetition rates. For this purpose, different analytical models of the detector response are evaluated, and validated by experimental data, to precisely retrieve the inherent detection efficiency for mean photon numbers covering three orders of magnitude as well as for laser repetition frequencies below and above the inverse detector dead time.

CONTRIBUTED TALKS
Mon 3rd July 2023

Borivoje Dakic, *University of Vienna (Austria)*
Quantum verification with few copies

Abstract:
As quantum technologies advance, the ability to engineer increasingly large quantum devices has experienced rapid development. In this context, verifying large entangled systems represents one of the main challenges in employing such systems for reliable quantum information processing. Though the most complete technique is undoubtedly full tomography, the inherent exponential increase of experimental and post-processing resources with system size makes this approach infeasible at even moderate scales. For this reason, there is currently an urgent need to develop novel methods that surpass these limitations. In this talk, I will review novel techniques [1] focusing on a fixed number of resources (sampling complexity) and thus prove suitable for systems of arbitrary dimension. Specifically, a probabilistic framework for single-copy for entanglement detection and few-copy device-independent quantum state verification is reviewed. I will also present the selective quantum state tomography method, which enables estimating arbitrary elements of an unknown state with several copies independently of the system’s size. These hyper-efficient techniques define a dimension demarcation for partial tomography and open a path for novel applications.
References
[1] J. Morris, V. Saggio, A. Gočanin and B. Dakić, Quantum Verification and Estimation with Few Copies, Adv. Quantum Technol. 2100118 (2022), https://doi.org/10.1002/qute.202100118.

Maria Bondani, *CNR-Institute for photonics and nanotechnologies (Italy)*
(Quantum) optics experiments to teach quantum physics in secondary schools

Abstract:
The role of secondary schools in promoting quantum awareness is crucial, as school curricula provide a common educational background for future scientists, technicians, policy makers and industrial leaders. However, simply organizing one-time events and seminars is not enough to achieve significant results. Instead, a comprehensive effort is needed to provide professional development for teachers, with the goal of facilitating curricular changes.
In Como, we have been working on teaching quantum physics in curricular and extracurricular activities with students and in in-service training courses for teachers since 2007. More recently, we have collaborated with other research groups in Italy to organize online extracurricular courses (2021-2022) and summer schools for interested students (2019-2023).
Our general methodology for engaging students and teachers focuses on experiments and simulators (when experiments are not available) and the interconnection between mathematical formalism and experimental demonstrations.
In the context of quantum science and technologies, real or even "analog" quantum experiments are difficult to implement in educational laboratories due to the complexity and cost of equipment. In this regard, optical phenomena exploiting different properties of light, such as polarization, can help construct meaningful experiments with reasonable effort and have been widely used in many programs on quantum technologies, both at the level of "single photon" and "macroscopic" light intensity.
The mathematical formalism needed to describe the experiments exploits some mathematical concepts that are covered in the Italian high school science curriculum, such as complex numbers, vectors and matrices, which are introduced and reworked in the context of laboratory activities. The potential of mathematical formalism is presented as a tool not only for interpreting and describing phenomena, but also for designing new experiments and predicting their possible results.

In the case of polarization, for example, the link between physical phenomenon and mathematical formalism is expressed through the parallelism between given physical devices (polarizer, waveplates) and the mathematical tools (matrices and vectors) used to describe their operation and interpret the results of experiments. The description of the interaction of light with the devices is then modeled as a transformation operated by the matrix representing the polarizer on the (complex) vector representing the state of light (electric field of an electromagnetic wave).
Students' appropriation of skills in the use of mathematical formalism also enables them to address new areas of physics, such as the study of quantum states of light in the context of single-photon experiments.

Robert Loew, *University of Stuttgart (Germany)*

Nonlinear optics with hot atomic vapours

Abstract:
The research and the spectroscopy of hot vapors carries great potential, ranging from fundamental research to robust applications in the context of quantum technologies.
In the past decades the spectroscopy of atomic and molecular gases at room temperature has lost some attention due to the focus on cold atomic systems. Still, due to their experimental simplicity, their robustness, and their fundamental nature, they hold the promise to realize real-world quantum devices. Their narrow-band transitions and high optical depths enable such vapor cell science to implement excellent sensors, references, metrologic devices or building blocks in quantum optics.
In this talk I will focus on optical non-linearities induced by atom-atom interactions, either by highly excited Rydberg states or for low lying states via the resonant dipole-dipole interaction. These non-linearities are manifest at the single photon level and can be exploited to generate and process non-linear light fields. As a platform we us a variety of cell types and excitation schemes, where the most advanced ones involve integrated photonic waveguides and microresonators.

Alberto Barchielli, *INFN Milano (Italy)*

Quasifree Markovian dynamics for quantum-classical hybrid systems

Abstract:
(from a joint work with R.H. Werner, in preparation)
Hybrid systems include a large class of dynamical systems and phenomena (see L. Dammeier, R.F. Werner, Quantum-classical hybrid systems and their quasifree transformations, arxiv:2208.05020 (2022)). From the "quantum" point of view, they include
"measurements" (the observed output signal is classical) and feedback-control situations (the classical systems send information to the quantum one by providing some inputs). In this talk I present results for a class of joint dynamics:
(a) Markovian case (no memory),
(b) continuous variables for both subsystems,
(c) quasifree operations, which means that, in the Heisenberg picture, quantum-classical Weyl operators are mapped to multiples of Weyl operators.

A quasifree dynamics is more general than the Gaussian case, which is included. The most general structure of a quasifree hybrid dynamical semigroup has been obtained; it presents analogies with the classical Lévy-Khintchine formula and contains a Gaussian
contribution and a jump part.
In the talk I will present the hybrid analog of the Lévy-Khintchine formula with applications to quantum measurements in continuous time, stochastic quantum master equations, feedback on a quantum system...
An interesting point is that, while the full hybrid dynamics is Markovian, this is not true for the reduced dynamics of the quantum component. So, we have the explicit expression of a class of non-Markov dynamics for an open quantum system.

Lewis Clark, *Centre of New Technologies, University of Warsaw (Poland)*

Exploiting non-linear effects in optomechanical sensors with continuous photon-counting

Abstract:
Optomechanical systems are rapidly becoming one of the most promising platforms for observing quantum behaviour, especially at the macroscopic level [1]. Moreover, thanks to their state-of-the-art methods of fabrication, they may now enter regimes of non-linear interactions between their constituent mechanical and optical degrees of freedom [2]. In this work, we show how this novel opportunity may serve to construct a new generation of optomechanical sensors [3]. We consider the canonical optomechanical setup with the detection scheme being based on time-resolved counting of photons leaking from the cavity. By performing simulations and resorting to Bayesian inference, we demonstrate that the photon statistics can be used to infer the value of an unknown system parameter, such as the optomechanical coupling strength.
Moreover, if the driving of an optomechanical system is (red) detuned, non-classical photon statistics occur within the non-linear regime [4]. Depending on the detuning taken, this may lead to either a photon blockade or photon cascades. By considering the non-classical correlations of the detected photons, we find that this may enhance the sensor performance in real time. As such, we are able to sense an unknown parameter highly accurately, even from a single quantum trajectory with imperfect photon detection and with a mechanical oscillator at non-zero temperature. We believe that our work may stimulate a new direction in the design of such devices, while our methods apply also to other platforms exploiting non-linear light-matter interactions and photon detection.

A limiting factor in the application of our Bayesian inference scheme is the computational time required to analyse a trajectory for such a complex system. To overcome this, we also overview how this can be circumvented somewhat by means of sampling. This provides a much more computationally efficient way of performing estimation and thus leads to an increase in the speed at which results can be obtained.

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[3] L. A. Clark, B. Markowicz and J. Kolodynski, Quantum 6, 812 (2022).
[4] A. Kronwald, M. Ludwig, and F. Marquardt, Phys. Rev. A 87, 013847 (2013).

Ilaria Gianani, *Università degli Studi Roma Tre (Italy)*

Continuous-time Quantum Walk recognition through machine learning

Abstract:
In the context of quantum technologies, networks constitute the prime structure of communication and computation protocols. Understanding how quantum information can be reliably transmitted between distant nodes of a network, or routed among different computational units, is a key step and requires a full characterization of the network's structure. While a direct control may not be attainable with the required accuracy and precision, a straightforward strategy to provide such characterization is that of probing the network with a walker that gathers information on its topology by undergoing an evolution which depends on the network's structure. This is the case of continuous-time quantum walks (CTQWs), which thus emerge as a natural paradigm for tackling this task.
Two different scenarios may present: the topology of the network may be known, but an accurate estimation of the coupling strengths between each node may be required. This is tantamount to estimating multiple parameters, and can be address in quantum metrological terms. In the estimation framework, Neural Networks have demonstrated to achieve superior performance in terms of reliability with finite-size dataset and robustness to noise compared to standard estimators. We will hence be following this route to study the characterization of CTQWs for a fixed topology, specifically for a CTQW unfolding on a line graph with n-neighbor interactions. Our results show that our model acts as a nearly optimal estimator, saturating the bounds established by the estimation theory.

It might otherwise be the case that the topology of the network is not known in advance. In this instance, the parameter space becomes exceedingly large for this to be treated as an estimation problem. A possible route is that of casting the issue in terms of a search problem instead. Having access solely to the initial state of the probe and to the measured experimental distributions at fixed times, the task becomes that of finding an adjacency matrix that matches the evolution. We tackle this by using a genetic algorithm. We show that it is possible to employ a genetic algorithm to successfully retrieve different topologies in the ideal case as well as when the measured probabilities are affected by noise.

Enrico Prati, *University of Milan (Italy)*

Erbium-Doped Nanodiode Integrated in a Silicon Photonic Waveguide for Room Temperature Few Photon Emission at 1550 nm

Abstract:
Recent advancements in quantum key distribution (QKD) protocols opened the chance to exploit nonlaser sources for their implementation. A possible solution might consist in erbium-doped light emitting diodes (LEDs), which are able to produce photons in the third communication window, with a wavelength around 1550 nm. Here, we present silicon LEDs based on the electroluminescence of Er:O complexes in Si. Such sources are fabricated with a fully-compatible CMOS process on a 220 nm-thick silicon-on-insulator (SOI) wafer, the common standard in silicon photonics [1]. Nanodiodes emit direclty in a silicon photonic waveguide. The implantation depth is tuned to match the center of the silicon layer. The erbium and oxygen co-doping ratio is tuned to optimize the electroluminescence signal. We fabricate a batch of Er:O diodes with surface areas ranging from 480 nm × 480 nm to 50 μm × 50 μm emitting 1540 nm photons at room temperature. We demonstrate emission rates around 5 × 10^6 photons/s for smallest devices at room temperature using superconducting nanowire detectors cooled at 0.8 K. The demonstration of Er:O diodes integrated in the 220 nm SOI platform paves the way towards the creation of integrated silicon photon sources suitable for arbitrary-statistic-tolerant QKD protocols.
[1] TAVANI, Giulio, et al. Fully Integrated Silicon Photonic Erbium-Doped Nanodiode for Few Photon Emission at Telecom Wavelengths. Materials, 2023, 16.6: 2344.

Matteo Rossi, *Algorithmiq Ltd (Finland)*

Self-consistent tomography based on semidefinite programming for quantum device characterization

Abstract:
Characterization of measurements and state preparation is a crucial task when perfoming experiments on quantum devices. In this work, we focus propose an estimation method for quantum measurement tomography (QMT) based on a semidefinite program (SDP), and discuss how it may be employed to detect experimental errors, such as shot noise and/or faulty preparation of the input states on near-term quantum computers. Moreover, we put forward a method for self-consistent tomography, i.e., for recovering a set of input states and POVM effects that is consistent with the experimental outcomes and does not assume any a priori knowledge about the input states of the tomography. Contrary to other methods discussed in the literature, our method does not rely on additional assumptions such as low noise or the existence of a reliable subset of input states. Finally, we discuss how this method can be extended to gate set tomography (GST) and to finite-shot tomography.

Marco Cattaneo, Elsi-Mari Borrelli, Guillermo García-Pérez, Matteo A. C. Rossi, Zoltán Zimborás, Daniel Cavalcanti, Semidefinite programming for self-consistent quantum measurement tomography, arXiv:2212.10262

Davide Girolami, *Politecnico di Torino (Italy)*

Quantitative bounds to propagation of quantum correlations in many-body systems

Abstract:
We quantify how much information about a quantum system can be simultaneously communicated to a network of observers, by establishing quantitative limits to bipartite quantum correlations in many-body systems.
Bounds on quantum discord and entanglement of formation between a single quantum system and its environment, e.g. a large number of photons, dictate that independent observers which monitor environment fragments inevitably eavesdrop only classical information about the system. The result validates the core idea of Quantum Darwinism: classical objectivity is not accidental, but rather a compelling feature of quantum theory.
Also, we recast an information-theoretic signature of classical objectivity in analytical form by means of the conditional mutual information, enabling one to monitor without hard numerical optimizations when objective reality emerges from the quantum substrate.
References:
D. Girolami, A. Touil, B. Yan, S. Deffner, W. Zurek, PRL 129, 010401 (2022)
A. Touil, B. Yan, D. Girolami, S. Deffner, W. Zurek, PRL 128, 010401 (2022)

Giorgio Zicari, *Queen's University Belfast (United Kingdom)*

On the role of initial coherence and correlations in the phase-space entropy production rate

Abstract:
Entropy production plays a pivotal role in characterising the irreversibility of a physical process [1]. This applies to the case of open quantum systems as well, where the irreversibility is inherently brought about by the interaction between the system and the environment.
The theory of entropy production for open quantum systems, whenever one relies on the standard Born-Markov approximation, is usually expressed using von Neumann entropy. However, the use of such an entropy might lead to inconsistencies, e.g., when dealing with pure states.
It has been shown that one way to remove these inconsistencies it to rely on the tools provided by quantum optics. One can indeed define an entropy over the phase space, either using the Wigner function (for bosonic systems) or the Husimi-Q function (for spin systems) [2,3].
We show that this semi-classical formalism can be used to thoroughly study the role played by quantum coherence and/or correlations in the entropy production rate [4,5]. In particular, we discuss under which conditions one can recover a monotonicity relationship between the figure of merit characterising the initial coherence (or the initial entanglement) and the entropy production rate.

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Tue 4th July 2023

Vladyslav Usenko, *Palacký University (Czech Republic)*

Multiplexed continuous-variable quantum communication with a linear cross talk

Abstract:
We address the multiplexed quantum communication scheme based on two-mode squeezed vacuum states and homodyne detection in the presence of linear cross talk between the. First, we theoretically consider two entangled mode pairs, so that two modes are measured locally, and other two modes interact in the source and are sent through an attenuating and noisy channel to a remote party. We study the distribution of entangled resource and continuous-variable quantum key distribution (CV QKD), using such scheme. We show how entanglement is degraded by the channel attenuation and that this effect is enforced by the presence of cross talk. Importantly, the effect of cross talk is related to the state variance, which should be then reduced and optimized to improve entanglement distribution. We also study the efficiency and robustness of CV QKD using multimode states with cross talk, by analyzing the asymptotic lower bound on the key rate in the reverse reconciliation scheme and evaluating the maximum tolerable level of the channel noise. We show that the tolerable noise is similarly degraded by the cross talk but can be maximized by optimally choosing the initial state variance. We then suggest applying a phase flip and reverse coupling prior to detection to compensate the negative effect of cross talk. We compare such deterministic interferometric scheme to an alternative one, based on the measurement on one pair of modes and feed-forward control of another pair, able to concentrate entanglement or key rate in the remaining pair of modes. We show that interferometric scheme for compensation of linear cross talk can either fully remove it, if the channel transmittance is the same for both the modes, hence completely restoring the entangled resources and QKD, or can optimally almost remove it once the transmittance is different [1]. Importantly, for QKD such decoupling of cross talk can be performed on the data after the measurement process, which we demonstrate on the experimentally characterized source of eight entangled mode pairs. We show that by optimally constructing a data processing scheme, equivalent to a linear-optical network, we can increase the key rate by almost a factor of 15 or extend the secure distance by cca. 100 km in a telecom fiber [2]. Our results pave the way to realization of multiplexed continuous-variable quantum communication.

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Tiff Brydges, *University of Geneva (Switzerland)*

Integrated Photonics for Quantum Repeater Networks

Abstract:
A key component of quantum communication is the distribution of entanglement through networks, however this comes with several challenges. One of the most significant is that direct distribution of entanglement between two nodes via a standard fibre link is unfeasible for transmission distances of more than a few hundred kilometres [1]. A solution is the ‘quantum repeater’ architecture, which distributes entanglement between two nodes via an intermediate repeater node [2].
Current state of the art experiments have recently implemented proof-of-principle, repeater-like networks with quantum memories [3]. However, such experiments often use highly complicated photon sources, which is impractical when moving towards a realistically implementable and scalable quantum network. Integrated photonics is a promising solution to this problem, allowing large numbers of components to be packaged together in a compact and stable manner. In particular, integrated micro-ring resonators (MRRs) have shown they are well-suited to the production of narrow-band photons, with bandwidths compatible with some rare-earth ion quantum memories [4, 5]. However, in moving towards stable and robust implementations of quantum networks, a source of photons which has the ability for high-bandwidth frequency tuning will be critical. Until

now, frequency tuning of photon-pairs generated by MRRs has only been demonstrated using thermal control, which has limited actuation bandwidth and is incompatible with cryogenic environments.

This talk will showcase our recent work at the University of Geneva, in collaboration with EPFL and Purdue University, on an entangled photon-pair source, based on a photonic integrated silicon nitride MRR with monolithically integrated piezoelectric frequency tuning. Results from fast-frequency locking of the MRR will be shown, with a resulting locking bandwidth many times higher than achievable with thermal locking schemes. Further, a novel demonstration locking the pump laser to the MRR through self-modulation of the MRR itself shows just some of the many abilities of this technology [6]. These abilities will have direct application in future schemes which interface such sources with quantum memories based on e.g. rare-earth ion schemes. Our work was recently accepted for publication in Physical Review A.

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Tommaso Tufarelli, *University of Nottingham (United Kingdom)*
Enhancement of light-matter interaction for a single emitter

Abstract:
Coupling N identical emitters to the same field is a well-established method to enhance light matter interaction. However, the resulting sqrt(N) boost of the coupling strength comes at the cost of a "linearized" (effectively semi-classical) dynamics. Here, we instead demonstrate a new approach for enhancing the coupling constant of a single quantum emitter, while retaining the nonlinear character of the light-matter interaction. We consider a single quantum emitter with N nearly degenerate transitions that are collectively coupled to the same field mode. We show that in such conditions an effective Jaynes-Cummings model emerges, with a boosted coupling constant of order sqrt(N). With a variety of analytical and numerical approaches, we then investigate the robustness of the approach in realistic conditions.
Reference: Phys. Rev. Research 3, 033103 (2021)

Ling Zhou, *Dalian University of Technology (China)*
Some quantum processes in hybrid cavity magnonics system

Abstract:
A yttrium iron garnet (YIG) sphere contained in the microwave cavity, or a YIG sphere coupling with nanofiber, forms a cavity-magnonics system. The cavity- magnonics system has recently emerged as a promising candidate for quantum information processing because of its ultrastrong microwave photon-magnon coupling and the long life of the magnon and phonon. We introduce a single two-level atom into the optomechanical-magnetic system and show that an unconventional blockade due to destructive interference cannot offer a blockade of both the photon and magnon. However, under the condition of single excitation resonance, the blockade of the photon, phonon, and magnon can be achieved simultaneously even in a weak optomechanical region [1]. We propose a scheme to achieve the nonreciprocal amplification in a hybrid cavity magnonics system. Owing to the gain and dissipation, the eigenvalues of the effective Hamiltonian exhibit exceptional points (EPs). We investigate the relation between EPs and the nonreciprocal amplification transmission and find that EPs can help us understand the amplification transmission as well as find the optimized parameters [2]. In order to perform quantum processing using YIG sphere, the mechanical mode of the YIG sphere should

be cooled to its ground-state.In a cavity-magnomechanical tripartite interaction system, we consider the magnetic thermal noise as an incoherent drive to facilitate cooling [3].
We simulate the extended Su-Schrieffer-Heeger model by using the hybrid cavity magnon system and investigate the distribution of edge states and the topological phase transition. We also discuss the transfer of the magnon entangled state [4]. In [5], we propose a scheme to enhance entanglement and asymmetric steering between two mechanical oscillators in an optomechanical system with coherent feedback control. Actually, this strategy also can be applied for microwave cavity contained two YIG spheres with a assitant feedback cavity.

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Francesco Pepe, *Università di Bari (Italy)*

Finite-size and multimerization effects in an array of emitters coupled to a waveguide

Abstract:

We present the features of a system of two-level quantum emitters, coupled to a single transverse mode of a closed waveguide, in which photon wavenumbers and frequencies are discretized, and characterize the states in which one excitation is steadily shared between the field and the emitters. We quantify finite-size effects in the field-emitter interactions and identify a family of dressed bound states that represent the forerunners of bound states in the continuum. For these states, we discuss possible applications in the field of quantum information. We conclude by showing that, in the limit of infinite-length waveguide, we detect the occurrence of multimerized bound states for multi-emitter arrays.

Maryam Khanahmadi, *Chalmers University of Technology (Sweden)*

The Multimode Character of Quantum States Released from a Superconducting Cavity

Abstract:

Quantum state transfer by propagating wave packets of electromagnetic radiation requires tunable couplings between the sending and receiving quantum systems and the propagation channel or waveguide. Tunability is sometimes obtained by a nonlinear interaction, and the resulting non-linear dynamics correlates the photon number and spatio-temporal degrees of freedom and leads to a multi-mode output state. In this work, we study as a specific example the release of complex quantum states from a superconducting resonator, employing a flux tunable coupler to engineer and control the release process. We quantify the multi-mode character of the output state and discuss how to optimize the fidelity of a quantum state transfer process with this in mind.

Zhihai Wang, *Northeast Normal University (China)*

Supercorrelated Radiance in Nonlinear Photonic Waveguides

Abstract:

We study the collective decay of two-level emitters coupled to a nonlinear waveguide, for example, a nanophotonic lattice or a superconducting resonator array with strong photon-photon interactions. Under these conditions, a new decay channel into bound photon pairs emerges, through which spatial correlations between emitters are established by regular interference as well as interactions between the photons. We derive an effective Markovian theory to model the resulting decay dynamics of an arbitrary distribution of emitters and identify collective effects beyond the usual phenomena of super- and subradiance. Specifically, in the limit of many close-by emitters, we find that the system undergoes a supercorrelated decay process where all the emitters are either in the excited state or in the ground state but not in any of the intermediate states. The predicted effects can be probed in state-of-the-art waveguide QED experiments and provide a striking example of how the dynamics of open quantum systems can be modified by many-body effects in a nonharmonic environment.

Karolina Słowik, *Nicolaus Copernicus University (Poland)*

Interfacing quantum optics with material science: Optics of graphene nanoflakes with adatoms

Abstract:
Low-dimensional material structures, such as 1D atomic chains or 2D nanoflakes, possess a plethora of electronic, optical, and material properties that are contingent on their chemical compounds and geometry. These properties make them ideal building blocks for multilayered heterostructures, which enable the realization of nanoscaled optoelectronics. Furthermore, the unique topological and plasmonic optical responses of these structures can be fine-tuned via electronic or optical manipulation.=
One such example of a low-dimensional material structure are graphene nanoantennas, which sustain strong electromagnetic field localization upon resonant illumination. To exploit the local field enhancement, it is crucial to position quantum emitters such as atoms or molecules close to the flake, where electron tunnelling may influence the optical response of the system. By leveraging the properties of low-dimensional structures such as graphene nanoantennas, more efficient and versatile nanophotonic devices can be developed with implications for fields such as quantum computing and optoelectronics.
Our work presents a framework for describing the electron dynamics in hybrid systems consisting of graphene nanoantennas coupled both electronically and optically to quantum emitters and subject to external illumination [1,2]. Specifically, our framework combines the single-particle tight-binding approach with a nonlinear master equation formalism that captures both optical and electronic interactions. Despite its relative simplicity compared to other approaches, our single-particle framework captures the physical essence of the material and enables the study of electron dynamics and the optical response of nanoantennas containing even hundreds of atoms. However, Coulomb interactions are implemented as nonlinearities through a density-matrix-dependent Hamiltonian.
We apply our framework to demonstrate the impact of electron tunnelling between the quantum emitter and the nanoantenna on emblematic quantum optical phenomena such as the degradation of coherent Rabi oscillations and quenching of Purcell spontaneous emission enhancement in two-level emitters in the proximity of graphene nanoantennas [2]. By providing insight into these phenomena, our work contributes to the development of more efficient and versatile nanophotonic devices with implications for fields such as quantum computing and optoelectronics.

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Ivo Pietro Degiovanni, *INRIM (Italy)*

Noise diagnostics by repeated quantum measurements

Abstract:
Quantum control [1] is a fundamental tool for quantum technologies. In particular, the quantum Zeno effect (QZE) [2] and anti-Zeno effect (AZE) [3,4], respectively, denoting the slowdown and speedup of quantum system evolution by its frequent interruptions [5], have been recognized (beyond their fundamental

significance) as quantum control paradigms [6,7]. Indeed, they allow either protecting or steering the quantum system state via an interplay between frequent operations (system control) and the coupling of the system to its environment.
Here we present two experiments carried on in INRIM labs where we demonstrate ability to extract information on noise processes. In the first case, we demonstrate experimentally for the first time noise diagnostics by repeated quantum measurements, showing how a single photon undergoing random polarization fluctuations can diagnose non-Markovian noise temporal correlations [8]. Such a technique may be indispensable under extremely faint illumination, when traditional interferometric methods are usually ineffective.
In the second case, we show that the quantum state protection mechanism, used e.g. in Ref. [9], can be exploited also a noise sensing technique to estimate the statistical behaviour of decoherence effects affecting the propagation of photonic qubits in a noisy quantum channel [10].

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Valeria Cimini, *Sapienza Università di Roma (Italy)*

Deep reinforcement learning for quantum sensing

Abstract:
Quantum sensing represents one of the most appealing quantum technologies. In particular, the possibility to perform the simultaneous estimation of multiple parameters beating the best possible precision achievable with classical resources represents an important step toward the application of quantum sensing to real-case scenarios. However, the larger the parameters' space is the harder it gets to characterize the operation of the sensor, a task that is necessary for its optimal use.
The identification of the optimal working point of quantum sensors is far from being trivial especially for high-dimensional quantum systems as in the case of multiparameter estimation problems. Usually, the employed optimization algorithms are extremely time-consuming since they have to be computed after each measurement outcome and, more importantly, they rely on the knowledge of the model of the operating device. In this work, we overcome this fundamental challenge by developing a Reinforcement Learning (RL) protocol, trained to choose the optimal control feedbacks, combined with a deep Neural Network (NN) architecture which updates the knowledge on the parameters' values, in the actual noisy multiparameter estimation experiment giving an estimate of the parameters of interest. Since the training of both these NN based algorithms is performed directly on the experimental data we do not need to rely on the sensor response function.

The control feedbacks chosen by the RL agent allowed us to demonstrate that the estimation precision reached using such deep learning protocols approaches the quantum Cramér-Rao bound already after the measurement of few probe states. We have implemented such an automated protocol thanks to the use of a programmable integrated photonic circuit which allows the controlling of the input states, as well as the performed measurements, easily configuring the control parameters to implement adaptive protocols in a fully black-box fashion. We experimentally demonstrate the goodness of the estimation performances achieved in the simultaneous estimation of three optical phases embedded in the four-arm integrated interferometer when it is injected with two undistinguishable photon probes.

Ivano Ruo-Berchera, *INRIM (Italy)*

Quantum-Enhanced Pattern Recognition

Abstract:
The theoretical and experimental development of quantum reading has demonstrated that the readout of bits encoded in the cells of an optical memory can be dramatically enhanced through the use of quantum resources (namely entangled input-states) over that of the best classical strategies [1,2]. This has stimulated other interesting quantum enhanced protocols based on bosonic-loss discrimination, such as test of conformance of production processes [3]. However, until now, experimental demonstrations have been limited to individual cells, while the practicality of this quantum advantage hinges upon the scalability of quantum sensing enhancement to the more complex multi-cell scenarios.
Here, we fill this gap by reporting the experimental expansion of quantum reading into the domain of pattern recognition [4].
The challenge of pattern recognition is to invoke a strategy that can accurately extract global features from a large dataset and classify its samples. One example, often used as testbed for classical advanced post-processing and machine learning, is handwritten digit recognition. We report the use of entangled probe states and photon-counting to achieve quantum-advantage in classification error over that achieved with any classical resources.
Our experimental findings confirm that advantage gained through quantum sensors can be sustained throughout complex post-processing [4]. Our results show how in certain ranges of the parameters space the advantage in the sensing is even amplified in the classification task, due to the highly non-linear features of post-processing algorithms. This paves the way for future developments of quantum-enhanced bosonic loss pattern recognition towards relevant applications and motivates future investigation on the performance of other quantum-enhanced sensing schemes within complex domains.

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Wed 5th July 2023

Alexander Sergienko, *Boston University (United States)*

Higher-Dimensional Hong-Ou-Mandel Effect with Linear-Optical Grover Multiports

Abstract:
We expand traditional two-photon Hong-Ou-Mandel (HOM) effect onto a higher-dimensional set of spatial modes and introduce a quantum network router providing controllable redistribution of entangled-photon states over four modes using directionally unbiased linear-optical Grover four-ports.
The Hong-Ou-Mandel (HOM) effect is one of the most recognized quantum two-photon interference effects [1]. When two indistinguishable photons arrive simultaneously at different inputs of a 50:50 beam splitter (BS), single-photon amplitudes at each output cancel, resulting in quantum superposition of two-photon states appearing at each output port. This traditional HOM method, observed on a beam-splitter with two input and two output ports, always has the two-photon state simultaneously occupying both output spatial modes, leaving no room to control the propagation direction. Entangled state propagation control is especially crucial in a large optical network to distribute quantum states between multiple parties. The state manipulation schemes we present can be integrated in quantum communication protocols. We propose two-photon quantum state engineering and transportation methods resulting in a linear-optical switch /router which allows manipulation of photon amplitudes in four spatial modes by using directionally unbiased linear-optical devices such as Grover coin optical multiports, beam splitters, and phase shifters [2,3].
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Antonio Mandarino, *ICTQT, University of Gdansk (Poland)*

Bell-Nonclassicality of a single photon

Abstract:
The Bell nonclassicality of a single-photon in superposition in two modes, aka “nonlocality of a single photon,” is one of the most striking nonclassical phenomena discussed in the context of foundations of quantum physics. We show how to violate local realism with weak-field homodyne measurements for any superposition of one photon with the vacuum. Our modification of the previously proposed setups involves tunable beam splitters, and weak local oscillator fields. As photon-number-resolving measurements are now feasible, we use of the Clauser-Horne Bell inequalities for detection events defined by a fixed numbers of photons and we find a condition for optimal measurement settings leading to a maximal violation of local realism, this states that the reflectivity of the local beam splitter must be equal to the strength of the local oscillator field. We show that this condition holds not only for the vacuum–one-photon qubit input state, but also for the superposition of a photon pair with vacuum, which suggests its generality as a property of weak-field homodyne detection with photon-number resolution.

Nicolas Fabre, Telecom Paris (France)

Time-frequency Quantum metrology

Abstract:
Hong-Ou-Mandel interferometry takes advantage of the quantum nature of two-photon interference to increase the resolution of precision measurements of time delays. Relying on few-photon probe states, this approach is applicable also in cases of extremely sensible samples and it achieves attosecond-scale resolution, which is relevant to cell biology and two-dimensional materials. Here, we theoretically analyze how the precision of Hong-Ou- Mandel interferometers can be significantly improved by engineering the spectral distribution of two-photon probe states. In particular, we assess the metrological power of different classes of biphoton states with non-Gaussian time-frequency spectral distributions, considering the estimation of both time and frequency shifts. We find that grid states, characterized by a periodic structure of peaks in the chronocyclic Wigner function, can outperform standard biphoton states in sensing applications.
After discussing the spectral engineering of photon pairs, we will discuss the use of more general quantum states possessing a higher number of photons for estimating time shifts using the presented intrinsic multimode quantum metrology approach. We will show that the particle-number and time-frequency degree of freedom are intertwined for quantifying the ultimate precision achievable by quantum means. Increasing the number of photons of a large entangled EPR probe state actually increases the noise coming from the frequency continuous variable hence deteriorating the precision over the estimation of a time shift.

Jan Kołodyński, *University of Warsaw (Poland)*

Enhancing quantum sensors by exploiting the non-Hermitian description of their dynamics

Abstract:
Describing the evolution of quantum systems by means of non-Hermitian generators opens a new avenue to explore the unique dynamical properties naturally emerging in such a picture [1], e.g. operation at the so-called exceptional points, preservation of parity-time symmetry, or capitalising on the singular behaviour of the dynamics. Such quantum features, in particular, have been demonstrated to strongly enhance the performance of non-Hermitian systems when operated as sensors [2,3].
In our fresh work [4], we focus on the possibility of achieving unbounded sensitivity when using the system to sense linear perturbations away from a singular point. By combining multiparameter estimation theory of Gaussian quantum systems with the one of singular-matrix perturbations, we introduce the necessary tools to study the ultimate limits on the precision attained by such singularity-tuned sensors. We identify under what conditions and at what rate can the resulting sensitivity indeed diverge, in order to show that nuisance parameters should be generally included in the analysis, as their presence may alter the scaling of the error with the estimated parameter.

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Roberto Di Candia, *Aalto University (Finland)*
Quantum Illumination with a Hetero-Homodyne Receiver and Sequential Detection

Abstract:
Quantum technologies exploting guided optics and integrated photonics represent a field in fully expansion due to the possibility of covering a wide panel of quantum light-based applications with miniaturized, reconfigurable and scalable architectures. In this talk, I will present our results on the development of telecom-compatible photonics solutions for long-range quantum communication as well as for the investigation of more fundamental quantum optical aspects. The generation and manipulation of quantum states of light will be discussed by presenting plug-n-play as well as integrated optics solutions relying on different technological platforms such as lithium niobate (LN) and silicon-nitride (SiN).

Athena Karsa, *Korea Research Institute of Standards and Science (Korea)*
Optimal quantum metrology for two-photon absorption

Abstract:
Two-photon absorption (TPA) is a crucial non-linear optical process with significant applications for quantum-enhanced imaging and spectroscopy. Despite this, the precise measurement and characterisation of TPA parameters is challenging due to the process' inherently weak nature alongside the discrete nature of light.
Quantum Fisher information (QFI) is employed to study the potential of quantum light to enhance TPA parameter estimation, leading to a fundamental precision bound through the quantum Cramer-Rao inequality. Discrete variable (DV) quantum states are optimised to maximise QFI for given losses, revealing a quantum advantage compared to the coherent state classical benchmark as well as the single-mode squeezed vacuum state.
For fixed energy, these optimal states take the form of Fock states for large TPA losses, and a superposition of vacuum and a particular Fock state for small losses. This differs from single-photon absorption where the Fock state is optimal across the entire range. Simple photon counting is also demonstrated to offer nearly optimal performance compared to the QFI bound for the studied states in a wide range of TPA losses.
Our findings provide further insight into the already-known limiting behaviours of Gaussian probes, and reasoning behind their different scaling under photon counting (~n^2 for squeezed vacuum states versus ~n^3 for coherent states). In particular, the squeezed state outperforms coherent states for small TPA losses but underperforms in the intermediate regime, becoming comparable in the large loss limit. This can be described by fundamental differences between behaviours of even and odd number Fock states across all possible values of loss: the QFI for even number states diverges in both large and small loss limits, while that for odd number states only diverges only in the small loss limit while dominating at intermediate scales. This work provides valuable insights into quantum-enhanced TPA parameter estimation, and paves the way for its potential application in TPA imaging techniques.

Julia Amoros Binefa, *– University of Warsaw (Poland)*
Quantum atomic sensors operated in real time

Abstract:
Optical magnetometers based on atomic spin-ensembles are considered today as state-of-the-art magnetic-field sensors competing head to head in sensitivity with SQUID-based devices without the need of cryogenic cooling.
When aiming to estimate a constant magnetic field, experiments have spectacularly demonstrated that sensitivities beyond SQL can be reached. In such experiments, the spin-ensemble is prepared in a spin-squeezed state every time before using it to sense the external magnetic field, which importantly cannot vary over the process of performing the necessary number of experimental repetitions.

The above paradigm, however, must be abandoned if the sensing task considered requires tracking of the magnetic field in real time, and one cannot assure the same magnitude of the field to be probed sufficiently many times. This may occur whenever the field follows a predetermined time-varying waveform subject to stochastic fluctuations, or its behaviour in time is simply not known at all. Still, the continuous quantum measurement theory allows one, in principle, to describe the dynamics of an optical magnetometer conditioned on the data collected in real time. Moreover, the Bayesian approach to estimation theory provides analogous tools to constrain the attainable "single-shot" precision—via the Bayesian Cramer-Rao Bound (BCRB).
In case of atomic magnetometry schemes in which spin-squeezing is realised continuously in time by light-probing based on the Faraday effect, the Bayesian inference techniques strikingly predict the average mean squared error (aMSE) to follow at short timescales the Heisenberg limit in absence of decoherence, 1/(t^3 N^2).
However, outside this limiting regime, a suitable and feasible estimation strategy for the magnetic field remained to be proposed, particularly in a non-ideal scenario with decoherence and field fluctuations present. Our work aims to provide a solution to this problem by proposing a novel strategy for estimating the magnetic field under such conditions.
First, we prove that decoherence and field fluctuations impose a lower bound on the sensitivity of our estimation, and we show that this ultimate bound can be achieved with our measurement strategy and initial state if we use Kalman filtering to obtain the optimal estimator in the Linear-Gaussian regime.
Outside this regime, we have found that a combination of an Extended Kalman Filtering with a measurement-based feedback is necessary in order to maintain the quantum-enhanced sensitivity or, in other words, drive the atomic ensemble into a highly entangled (spin-squeezed) state tailored to efficiently track a fluctuating magnetic field.

Wojciech Górecki, *INFN Pavia / University of Pavia (Italy)*

Using adaptiveness and causal superpositions against noise in quantum metrolog

Abstract:
We derive new bounds on achievable precision in the most general adaptive quantum metrological scenarios. The bounds are proven to be asymptotically saturable and equivalent to the known parallel scheme bounds in the limit of large number of channel uses. This completely solves a long standing conjecture in the field of quantum metrology on asymptotic equivalence between parallel and adaptive strategies. The new bounds also allow to easily assess the potential benefits of invoking the non-standard causal superposition strategies, for which we prove, similarly to the adaptive case, the lack of asymptotic advantage over the parallel ones.

Jesús Rubio Jiménez, *– University of Surrey (United Kingdom)*

Quantum scale metrology: highly precise measurements beyond phase estimation

Abstract:
Whether quantum technologies are ultimately successful will depend on our ability to perform highly precise measurements. This has led to an in-depth revision of the foundations of quantum metrology beyond the traditional framework of phase estimation. For instance, for regimes with finite data sets, incompatible estimators, and parameter types other than phases. In this talk, quantum scale metrology is established as the most precise framework for the estimation of scale parameters that is allowed by the laws of quantum mechanics. For given prior probability and quantum state, and using Bayesian principles, a rule to construct the optimal probability-operator measurement is identified. Moreover, the corresponding minimum mean logarithmic error is calculated. This is then generalised as to accommodate the simultaneous estimation of multiple scale parameters. As a means of illustration, the new framework is applied to the estimation of a lifetime for an atom undergoing spontaneous photon emission. Quantum scale metrology is thus argued to open a new line of enquire—the precise measurement of scale parameters such as rates and temperatures—within the quantum information sciences.

J. Rubio, Quantum Sci. Technol. 8 015009 (2022)

Giovanni Chesi, *INFN Pavia (Italy)*

Global multiphase quantum estimation

Abstract:
In principle, global estimation strategies allow to extract information on a phase or a set of phases without any prior knowledge about them. However, unlike the local estimation case, a global multiphase estimation strategy does not exist yet. We devised a protocol based on Holevo’s estimation theory that straightforwardly generalizes global single-phase estimation strategies to the multiphase scenario. We exploit our protocol to investigate the performance of multiphase global estimation in terms of mutual information and show that the advantage with respect to the repeated application of a single-phase estimation protocol amounts to a constant factor.

Marta Maria Marchese, *Universität Siegen (Germany)*

Large Baseline Optical Imaging Assisted by Single Photons and Linear Quantum Optics

Abstract:
In this work, we show that the combination of quantum metrology and networking tools allows for the baseline’s extension of interferometric optical telescopes. This causes an increase in the resolution of positioning incoherent point sources. We propose a protocol to achieve significant highly resolved images, where the quantum interferometer relies on multiple single-photon sources, optical fibres, linear optical circuits and efficient photon number-counting detectors. Surprisingly, even in presence of high transmission losses across the baseline, the Fisher information is mildly affected, and the protocol is still able to provide an enhancement in the imaging resolution. We obtained an improvement in the resolution of the order of 10 µas for thermal stellar sources consisting of low photon number per mode. The experimental implementation of our proposal would require currently available technology, without the need for quantum memories or quantum repeaters networks.

Thu 6th July 2023

Petr Marek, *Palacký University (Czech Republic)*

Nonlinear squeezing as a non-Gaussian resource for quantum technologies

Abstract:
Quantum non-Gaussianity was recently recognized as an important resource for CV quantum information processing, which is necessary for some of the advanced applications, such as quantum computation. The non-Gaussian features of quantum states, often tied to negativity of their Wigner function, are difficult to implement experimentally. The most common experimental sources rely on photon number resolving measurements or interactions with qubit systems, which are both probabilistic approaches. In past we have suggested that one of the elementary non-Gaussian operations, cubic phase gate, can be realized deterministically in a measurement induced fashion if a proper ancillary quantum state is used. This ancillary state possesses a novel kind of non-Gaussianity - the nonlinear squeezing - defined as reduction of variance of a nonlinear combination of quadrature operators. In contrast to vague indicators of non-Gaussianity such as the negativity of Wigner function which is only necessary, the nonlinear squeezing is a sufficient operationally defined quantifier of non-Gaussianity that is directly tied to the performance of the deterministic non-Gaussian circuit. In this contribution we present the basic theoretical concept and elementary behavior, several theoretical methods of preparation for quantum states with nonlinear squeezing, and the recent progress in experimental realization.

Célia Griffet, *Université libre de Bruxelles (Belgium)*

Accessing continuous-variable entanglement witnesses with multimode spin observables

Abstract:
We present several measurement schemes for accessing separability criteria for continuous-variable bipartite quantum systems. Starting from moments of the bosonic mode operators, criteria suitable to witness entanglement are expressed in terms of multimode spin observables via the Jordan-Schwinger map. These observables are typically defined over a few replicas of the state of interest and can be transformed into simple photon-number measurements by passive optical circuits. Our measurement schemes require only a handful of measurements, thereby allowing one to efficiently detect entanglement without the need for costly state tomography, as illustrated for a variety of physically relevant states (Gaussian, mixed Schrödinger cat, and NOON states). The influence of typical experimental imperfections is shown to be moderate.

Stephan De Bievre, *Université Lille (France)*

Assessing nonclassicality through the interferometric measurement of the quadrature coherence scale

Abstract:
Assessing whether a quantum state is nonclassical, meaning that it is not a mixture of coherent states, continues to be a ubiquitous question in quantum optics. Over the years, witnesses, measures and monotones of such nonclassicality have been designed, with different merits. The recently introduced quadrature coherence scale has been proven to have a number of advantages: it is not only an efficient witness, but also provides a measure of nonclassicality. In addition, it has a direct physical interpretation in terms of the decoherence time of the system [1-4]. The question remained if it can also be measured directly and easily. Since the expression of the QCS is not linear in the state of the system, but quadratic, it cannot be seen as the expectation value of an observable. Of course, a full tomography always allows one to determine the QCS through measurement and a post-treatment of the experimental data, but this is resource consuming and not

straightforward. In [5], we provide an experimentally friendly procedure for directly accessing the QCS using only a simple linear interferometer involving two replicas (independent and identical copies) of the state supplemented with photon number measurements. This finding, which we interpret as an extension of the Hong-Ou-Mandel effect, illustrates the wide applicability of the multicopy interferometric technique in order to circumvent state tomography in quantum optics. Our protocol has been experimentally tested with success on the Xanadu cloud computer [6].

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Annaelle Hertz, *National Research Council of Canada (Canada)*

Nonclassicality and quantum non-Gaussianity of photon-added/subtracted multi-mode Gaussian states

Abstract:
Gaussian states are prominent in continuous-variable quantum information but non-Gaussian states or operations are essential for performing certain quantum information tasks. Nevertheless, for a state to be non-Gaussian is not always enough for it to be interesting in the context of quantum information or quantum computing tasks. Indeed, non-Gaussian states may still be classical meaning that they may be mixtures of coherent states. Or they may be more generally mixtures of Gaussian states, in which case they are said not to be quantum non-Gaussian. Nonclassicality or the stronger property of quantum non-Gaussianity are needed for certain quantum informational tasks and a variety of techniques for their detection and measure have been developed. One possible method for producing non-Gaussian states is through photon addition or subtraction from a Gaussian state. In this talk, we provide a quantitative analysis of the degree to which the resulting states are nonclassical or quantum non-Gaussian. For our analysis, we will concentrate on two distinct measures of nonclassicality, namely their quadrature coherence scale (QCS) [1] and their Wigner negativity, as expressed through their Wigner negative volume [2]. Regarding the quantum non-Gaussianity, we will use a sufficient criterium on the value of the Wigner function at the origin, developed in [3].
Our results for single-mode states establish that the degaussification through photon addition/subtraction does substantially enhance the nonclassical features of the underlying Gaussian states. Importantly, these results also entail that the increased nonclassicality that is generated in the process comes at a cost. Indeed, the QCS is proportional to the decoherence rate of the state so that the resulting states are considerably more prone to environmental decoherence. Our results are quantitative and rely on explicit and general expressions for the characteristic and Wigner functions of photon added/subtracted single- and multi-mode Gaussian states for which we provide a simple and straightforward derivation. These expressions further allow us to identify a family of photon-subtracted Gaussian state with positive Wigner function that are quantum non-Gaussian.
This talk is based on a paper soon to appear in Phys. Rev. A [4].

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Polina Sharapova, *Paderborn University (Germany)*

Optomechanical SU(1,1) interferometer

Abstract:
Precision measurement is the primary building block for many physical applications and proof-of-concept experiments. In optics, the main measurement tool is interferometry, which, however, has a fundamental bound of precision (shot noise limit) when using classical light. The use of new types of interferometers, namely nonlinear SU(1,1) interferometers [B. Yurke et al., Phys. Rev. A 33, 4033 (1986)], makes it possible to overcome this bound. One of the important features of such interferometers is the strong correlations between the generated signal and idler photons. These correlations lead to the effect of induced coherence without induced emission [L. J. Wang et al., Phys. Rev. A 44, 4614 (1991)] and make it possible to provide a quantum imaging of undetected photons [G. Lemos, et al., Nature 512, 409–412 (2014)]. The concept of the SU(1,1) interferometer may go beyond the scope of optical realizations and be extended to other types of nonlinear interactions, such as atom-atom, phonon-phonon or hybrid atom-light and phonon-light interactions. In this work, we investigate an optomechanical SU(1,1) interferometer and demonstrate the protocol for measuring the phase of the mechanical object by detecting the intensity of light. The considered SU(1,1) interferometer is based on the interaction of light and a membrane placed inside the cavity. In contrast to conventional quantum optical interferometers, two correlated quanta of different origin, namely a photon and a phonon, are generated during each nonlinear interaction. Because of the strong correlations between the generated signal and idler quanta, measuring the output photons allows us to extract an information about the phase applied to the mechanical object, even if the photons have not undergone any phase shift. By providing temporal mode shaping and taking into account thermal noise at the room temperature, we demonstrate the phase sensitivity below the shot noise limit.

Anna Kowalewska-Kudłaszyk, *A. Mickiewicz University (Poland)*

Optical and hybrid opto-mechanical blockades

Abstract:
Blockades in bosonic systems are the analogs of well-known Coulomb blockades observed for electrons. It is referred to as a phenomenon in which the generation of a single (or two) bosons in an externally driven nonlinear system can block the generation of more bosons in the same system. There are multiple theoretical as well as experimental examples of such blockades in optical systems. They can be used for example as single photon sources. The possibility of obtaining single and two-photon blockades in an optical system in which nonlinearity is induced via squeezed reservoir will be presented [1]. Various types of correlations, related to the photon, phonon blockades, or photon-induced tunneling in optical, mechanical, and hybrid modes of the optomechanical system will also be discussed. This novel type of blockade in hybrid mode is generated by linear coupling between optical and mechanical modes [2].

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Fri 7th July 2023

Andrew White, *University of Queensland (Australia)*

Rise of the Machines: Making better photons by getting rid of experimentalists

Abstract:
There is now an enormous opportunity to interconnect quantum components together into complex, short- and long- range networks of sensing, communication, and computational elements. Photons are a natural choice for networking quantum technologies as their quantum nature survives at room temperature and long distance propagation is possible, either via optical fibre or through free space. Here we explore using machine learning (ML) to optimise production, coupling, routing, and circuitry for single photons. Our single-photon source platform is resonant excitation of individual quantum dots coupled to a micropillar cavity [1]. Multiphoton suppression in the quantum dot emission—as well as single-photon indistinguishability and brightness—are directly influenced by the spatiotemporal characteristics of the optical excitation pulses. We use ML techniques to tailor the excitation laser pulse properties in real-time, significantly reducing the search time for optimal parameters. We also employ ML to control a deformable mirror, correcting for aberration on the single-photon wavefront field to maximise the coupling between the source output and a single-mode fibre [2]. This combination provides a toolbox for enhancing the performance of any solid-state single-photon source. Photonic integrated circuits (PICS) will be essential for scalably realising photonic quantum technologies. Actively coupling photons into PICS requires high-fidelity integrated switches [3]. Current best practice—manual optimisation of electronic signals for each individual switch on a chip—is slow and unscalable. We use ML—simulated annealing—to optimise driving parameters for up to 4 switches on a single chip, achieving a significant speed up in tuning while retaining optimal performance. PICS often interface light in and out of the chip using edge coupling, which severely limits chip geometry as well as adding complication to fabrication. Using ML—inverse design [4]—we are developing efficient out-of-plane couplers and small-footprint waveguide crossings that are easier to manufacture and have higher circuit density. Our new architecture lowers entry costs for photonic integrated circuitry development, and we will ensure widespread adoption by disseminating to the community the full details of our designs and fabrication methodologies.

Emanuele Distante, *Max Planck Institute of Quantum Optics (Germany)*

A quantum network link based of single-atom cavity QED modules

Abstract:
In this talk, I will present our recent realization of a quantum network link made of single atoms trapped at the center of two optical resonators separated by 21 meters and connected via optical fibers. The resonator provides a very efficient light-matter interface that allows single atoms to interact with single photons. First, I will discuss how such a strong interaction allows us to measure the presence of a photon traveling within the network link without absorbing it [1]. Each single-atom cavity system realizes a quantum nondestructive detection of a photon, and I will show how we concatenate two of such systems to greatly increase the signal-to-noise ratio of the photon detection. Then I will discuss how we can encode qubits in the long-lived ground states of atoms and how we can use photons to realize a non-local quantum gate between largely separated qubits [2], which paves the way toward distributed quantum computing. Finally, I will show how optical photons can be used as ancillas to realize a complete Bells state projective measurement of distant qubits [3]. Compared to the standard realization of projective Bell state measurement based on linear optics and single-photon detectors, our scheme allows distinguishing between all four maximally entangled states.
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Kimin Park, *Palacký University (Czech Republic)*

Slowing quantum decoherence by hybrid processing

Abstract:
Quantum information encoded into the superposition of coherent states is an illustrative representation of practical applications of macroscopic quantum coherence possessing. However, these states are very sensitive to energy loss, losing their non-classical aspects of coherence very rapidly. An available deterministic strategy to slow down this decoherence process is to apply a Gaussian squeezing transformation prior to the loss as a protective step. In this talk, I will present a deterministic hybrid protection scheme utilizing strong but feasible interactions with two-level ancillas immune to spontaneous emission. We verify the robustness of the scheme against the dephasing of qubit ancilla. Our scheme is applicable to complex superpositions of coherent states in many oscillators, and remarkably, the robustness to loss is enhanced with the amplitude of the coherent states. This scheme can be realized in experiments with atoms, solid-state systems, and superconducting circuits.

Bruno Bellomo, *Université de Franche-Comté (France)*

Implementation of a continuous dynamical decoupling procedure to protect operations on qudits from noise

Abstract:
Studying methods to protect quantum systems from environmental noise is crucial for the development of quantum technologies. In this talk, I will present a protocol aiming to protect an ensemble of d-level systems (qudits), upon which acts an arbitrary multiqudit gate, from the detrimental effects of a general noise [1]. The protocol consists in a generalized continuous dynamical decoupling (GCDD) procedure making use of time-dependent external control fields. After presenting the GCDD procedure in the general case of an arbitrary qudit, I will focus on the specific case of a Hadamard gate acting on an atomic qutrit implemented using the three magnetic hyperfine states of the ground energy level of an 87Rb atom. The protection scheme makes use of laser beams, which can be characterized in terms of nine independent Rabi frequencies, whose intensities and phases are modulated according to our prescription. The effectiveness of the protection scheme will be discussed by means of numerical simulations. I will also show that this protection method can be extended to the case of an ensemble of arbitrary qudits perturbed by the interaction with an environment, which can contain both local and nonlocal terms. In the final part of the talk, I will present a study of the form required for the time-dependent Rabi frequencies involved in the GCDD procedure for the same atomic qutrit [2]. Several simulations will be considered to implement the protection of the action of different quantum gates, including randomly chosen ones. I will also discuss the transition from one gate operation to another, including the protection of a qutrit memory state, and apply our methodology to protect from noise the application of an algorithm capable of distinguishing the parity of permutations of three elements. It is argued that the requirements for the Rabi frequencies involved in this kind of protection schemes could be nowadays experimentally met.

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Dario Fioretto, *C2N, CNRS, Universite-Paris-Saclay (France)*
High-rate entanglement between a semiconductor spin and indistinguishable photons

Abstract:
Semiconductor quantum dots have shown excellent properties as single-photon sources, including record levels of brightness, purity and indistinguishability [1, 2]. Moreover addressing the spin of a confined charge carrier in the dot, whether electron or hole, through optical selection rules enables the generation of spin-photon and photon-photon entanglement. Most importantly, a theoretical scheme proposed in 2009 [3] showed that this entanglement can be harnessed with minimal resources to generate multi-photon entangled states such as linear cluster states or photonic GHZ. Those states are building blocks for measurement-based quantum computing and large scale quantum networks. However, obtaining high quantum purity and bright single-photon emission whilst maintaining access to the polarization of the emitted light – that are key to leverage on the spin degree of freedom in the entanglement protocol– remains challenging.
In this work [4], we build on two major milestones achieved in our group over the years. On the one hand, we use quantum dot confined in micropillar cavities that enables to achieve state-of-the-art level of brightness and is crucial to perform multiphoton experiments. On the other hand we exploit a phonon-assisted, off-resonant excitation scheme which preserves access to the polarization degree of freedom to produce entangled photons from an electron spin confined in a quantum dot, whilst maintaining efficient single-photon generation and high quantum purity. This driving scheme enabled us to probe the precession dynamics and characterize key parameter of the system. We pushed this technique further and exploit successive timed optical excitations of a precessing single spin to generate spin-multiphoton-entangled states. We demonstrate spin-photon entanglement and spin-photon-photon entanglement with fidelity respectively of 82% and 65% with indistinguishable photons (VHOM > 93%) and rates exceeding up to 3 orders of magnitude the state of the art. This milestone clears the path for scalable approaches for producing multidimensional cluster states, key resources for real world implementation of measurement-based quantum computation.
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Seibold Kilian, *University of Konstanz (Germany)*
Quantum dynamics of Dissipative Kerr solitons

Abstract:
https://journals.aps.org/pra/abstract/10.1103/PhysRevA.105.053530
Dissipative Kerr solitons arising from parametric gain in ring microresonators are usually described and understood within a classical mean-field framework. In this work, I develop a quantum-mechanical model of dissipative Kerr solitons in terms of the Lindblad master equation formalism and study the model via the truncated Wigner method, accouting for quantum effects to leading order in $hbar$.
In my talk, using the theory of open quantum systems, I will show that the solitons experience a finite coherence time due to quantum fluctuations originating from losses. The Liouvillian spectrum of the system is characterized by a set of eigenvalues with finite imaginary part and vanishing real part in the limit of vanishing quantum fluctuations. This arrangement emerges asymptotically in the limit of large input power, and the Liouvillian gap vanishes as a power law of the total photon occupation in the microring modes. This shows that DKSs are a specific manifestation of a dissipative time crystal --- a general phenomenon which can arise in open quantum systems and has been extensively studied in recent times. Establishing the link between DKSs

and dissipative time crystals is an important step in the study and characterization of spontaneous time-translational symmetry breaking in quantum systems out of equilibrium. While being a theoretical work per se, special consideration will be given to the experimetal implementations of the system under investigation.

Orsolya Kalman, *Wigner Research Centre for Physics (Hungary)*

Applications of iterated nonlinear quantum protocols

Abstract:

Nonlinear quantum dynamics can be generated by applying an entangling operation on a pair of copies of a quantum state and then projecting one of the outputs onto e.g. a given computational basis state. In this case, the unmeasured quantum system can evolve in a nonlinear way as compared to its initial state, thus, the corresponding procedure is termed a nonlinear quantum protocol. If one has an ensemble of copies, one can form pairs from the already nonlinearly transformed systems and then repeat the same procedure, i.e., iterate the protocol. By studying the corresponding mathematical formulation of such iterated dynamics, we designed nonlinear protocols which can perform useful quantum informational tasks such as discriminating nonorthogonal qubit states or deciding whether an unknown qubit state is in the prescribed neighborhood of a reference state. These dynamics can tolerate a high level of noise without losing their interesting features, which makes them a possible testing and benchmarking tool for current noisy quantum computers and potential platforms. Another possible application of such nonlinear quantum protocols is for two-qubit states as inputs. We found protocols which, in an LOCC setup, can produce perfect Bell pairs in a few iterations from any initially weakly entangled state, even if the input state contains some noise.

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Carlos Sánchez Muñoz, *Universidad Autónoma de Madrid (Spain)*

Dissipative generation of high stationary entanglement between non-identical quantum emitters

Abstract:

In order to entangle two quantum emitters, it is commonly considered that these should have identical natural frequencies to facilitate cross talk between them and enable collective dynamics [1]. The fabrication of emitters with identical natural frequencies is indeed regarded as one of the most important challenges for the scalability of on-chip quantum setups based on solid state quantum emitters. In this work, we show that non-identical quantum emitters in tailored dissipative environments, such as microcavities or waveguides, can be brought to stationary states of very high degree of entanglement, even if their detuning is much larger than their natural coupling rate or their losses. Crucially, this is achieved if both emitters are excited at the two-photon resonance, i.e., with a drive with half the frequency of the doubly-excited state [2,3]. For close emitters that are naturally strongly interacting, the combination of both a properly tuned cavity and two-photon drive leads to the stabilization of either the symmetric or antisymmetric combination of one-excitation qubit states, depending on the transition resonantly selected by the cavity. The degree of stationary entanglement produced in this way is much larger than the one obtained by direct, resonant excitation of the symmetric/antisymmetric states, as well as being a much faster and optically tunable process. On the other hand, for the case of non-interacting emitters, we show that the combination of two-photon drive and the enhancement of collective decay provided by a cavity or waveguide can stabilize, with very high probability, the antisymmetric single-excitation state. We prove that this stabilization of entanglement can be understood in terms of a recently reported mechanism of dissipative population of virtual states [4].

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Jorge G. Hirsch, *Instituto de Ciencias Nucleares, UNAM (Mexico)*
Chaos, scarring and localization in a spin-boson system

Abstract:
The Dicke model describes a system of N two-level atoms collectively coupled with a quantized field, characterized by one bosonic mode. It provides a description of the superradiance phenomenon in light-matter systems and is useful to understand nonequilibrium dynamics.
It has two classical degrees of freedom, and displays regular and chaotic dynamics, depending of the Hamiltonian parameters and the energy region analyzed.
We have recently employed this model to analyze the relationship between instability, classical chaos and the evolution of out-of-time-ordered correlators [Chavez2019,Pilatowsky2020]. We have also studied the presence of classical unstable periodic orbits. They are directly associated with the phenomenon of quantum scarring, which restricts the degree of delocalization of the eigenstates and leads to revivals in the dynamics [Villasenor2020,Pilatowsky2022].
Contrary to some common beliefs, we demonstrated that all eigenstates of the chaotic Dicke model are actually scarred. Even the most random states of this interacting atom-photon system never occupy more than half of the available phase space. For this reason, quantum ergodicity is achievable only as an ensemble property, after temporal averages are performed [Pilatowsky2021].

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POSTER PRESENTATIONS

POSTER SESSION 1, Wed 5th July 2023

Peter Adam, *Wigner Research Centre for Physics (Hungary)*

Spatially multiplexed single-photon sources based on incomplete binary-tree multiplexers with optimal structure

Abstract:
The development of single-photon sources (SPSs) is in the focus of research due to the numerous applications of such devices in the fields of quantum information processing and photonic quantum technology.

Multiplexed single-photon sources are promising candidates to yield indistinguishable single photons in near-perfect spatial modes with known polarization on demand [1].

One of the aims of the researches in this area is to find the multiplexing schemes that lead to the highest performance single-photon sources.

In this communication we discuss four novel types of spatially multiplexed single-photon sources based on output-extended incomplete binary-tree multiplexers containing general asymmetric routers [4] where the rule of placement of the novel photon routers during the construction is determined by the magnitudes of the losses of the optional connection points.

After selecting the multiplexer that outperforms the others, we analyze and optimize single-photon sources based on such systems using a general statistical theory that takes all relevant loss mechanisms into account [2] and compare these sources to the ones based on asymmetric multiplexers [3].

We determine the ranges of the loss parameters for which single-photon sources based on such systems yield higher single-photon probabilities and lower values of the second-order autocorrelation function characterizing the multiphoton noise than that can be achieved by using asymmetric multiplexers.

We find that the advantage of the proposed multiplexers appears for high values of the transmission coefficients characterizing single-photon sources having the best performance.

Finally, we conclude that these multiplexers can be used especially beneficially in single-mode single-photon sources characterized by thermal statistics of the input photon pairs and the application of them yields high performance single-photon sources even for suboptimal system sizes that is a typical situation in current experiments.

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Jessica Barr, *Queen's University Belfast (United Kingdom)*
Machine Learning-Enhanced Spectral Density Classification in Open Quantum Systems

Abstract:
In a standard open quantum system scenario, the relevant information characterising the system-environment interaction is encoded in a function, known as spectral density, whose accurate knowledge is essential to determine the system's dynamics. In this work, we leverage the potential of machine learning techniques to reconstruct the features of the environment. Specifically, we show that the time evolution of a system observable can be used by an artificial neural network to infer the main features of the spectral density. In particular, for relevant example of spin-boson models, we can classify with high accuracy the Ohmicity parameter of the environment as either Ohmic, sub-Ohmic or super-Ohmic, thereby distinguishing between different forms of dissipation.

Karol Bartkiewicz, *Adam Mickiewicz University (Poland)*
Quantum exceptional points of non-Hermitian systems via quantum process tomography

Abstract:
Hamiltonian exceptional points (HEPs) are degeneracies of non-Hermitian Hamiltonians for classical and semiclassical systems, which exhibit usually both dissipation and amplification. However, this definition ignores the effect of quantum jumps on the evolution of quantum systems. Quantum EPs (QEPs), defined as degeneracies of quantum Liouvillians, are natural generalizations of the standard semiclassical EPs by including the effect of quantum jumps [Minganti et al., Phys. Rev. A 100, 062131 (2019)]. Here we explicitly describe how standard quantum process tomography, which is a popular method to reveal the dynamics of a quantum system (a black box), can be readily applied for revealing and characterizing QEPs of non-Hermitian systems. We analyze prototype models to show how to tune their system parameters to observe QEPs. Specifically, we study systems of driven dissipative qubits. We show experimentally how reveal the same or different QEPs and HEPs.

Sherry Blair, *Queen's University Belfast (United Kingdom)*
Gate-based quantum computation in photonic platforms via GKP codes

Abstract:
Bosonic codes are an alternative and promising approach to quantum computation. Photonic platforms are being developed [1,2] which consist of a set of gates acting on vacua, but it is still unknown if such a platform can facilitate universal computation with bosonic codes. We prove that this is the case, with the Gottesman-Kitaev-Preskill (GKP) encoding [3]. Using the Strawberry Fields software [4,5], we construct a variational circuit comprised of a set of continuous-variable gates that can be implemented on photonic platforms. To generate the GKP states from vacua we use a machine learning method put forward by Arrazola et al. [6]. We show that the photonic circuit is capable of generating the states and performing the gates required for universal computation with the GKP code.

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Alexander Bott, *Institut für Quantenphysik and Center for Integrated Quantum Science and Technology, Ulm University (Germany)*

Light-matter interaction with single-photon transitions for sensing beyond the Standard Model

Abstract:
Atom interferometers have been successfully employed for high-precision measurements of various quantities, for instance accelerations as well as fundamental constants. Differential measurements with atom interferometers are a promising avenue for demanding sensing applications such as the detection of gravitational waves and light scalar dark matter. Most current atom interferometers rely on two-photon transitions used for Raman or Bragg diffraction. Single-photon transitions driven by a single laser are a hopeful alternative for such differential detectors as they offer a natural mitigation of laser phase noise.
In our contribution we derive an effective atomic two-level model for both Raman and single-photon transitions, including perturbations from effects beyond the Standard Model; in particular we include violations of the Einstein equivalence principle and effects of light scalar dark matter. We obtain a description of the time-evolution of such effective atomic two-level systems during their interaction with light. Therefore, we determine phase contributions imprinted by the Standard Model violations on the atoms interacting with the lasers in an atom interferometer.

Ambroise Boyer, *Sorbonne Université Laboratoire Kastler Brossel (France)*

A hybrid approach to improve linear photonic Bell-state measurement

Abstract:
Bell-state measurements are ubiquitous in quantum computation and communication protocols, e.g in swapping and teleportation schemes. In the optical domain one of the four Bell-state measurements consists in detecting one and only one photon. This measurement should enable to distinguish the one photon state from vacuum and multi-photon states. Limiting this multi-photon component is fundamental to improve the fidelity and the robustness to detection inefficiency of the measurement. Today, on-off detection is widely used but cannot resolve one photon from multiple ones, whereas photon number resolving is still in development. In this context, we report on an in-depth analysis of the benefits of a hybrid Bell-state-measurement (HBSM), which has been used effectively in both swapping [1] and teleportation [2] experiments.

This hybrid Bell-state measurement relies on the combination of homodyne conditioning and on-off detection. A two-photon event is detected as an error therefore boosting the fidelity of this measurement. A low-transmittivity beamsplitter is introduced, before the on-off detection, with the reflected part sent to the homodyne detection. In the limit of small transmittivity, a two-photon state would be split with high probability, leaving a single photon in the reflected path after the beamsplitter. This can now be detected as an error via the homodyne conditioning where we harness the different marginal distributions of vacuum and single-photon states. We compare the performances in fidelity, robustness to detection inefficiency and count rate, of our hybrid Bell-state measurement to on-off and photon number resolving detection.

In this contribution we will present this technique, including the associate POVM and its use for different applications. Its performances are studied as a function of the conditioning window of the homodyne detection, the reflectivity of the beamsplitter and the efficiency of the single photon detector. Finally, comparing to photon number resolving measurements based on SNSPDs with an efficiency lower than 0.90 (a typical value for SNSPDs), we show that this hybrid Bell-state measurement achieves better purity and fidelity.

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Patrick Cameron, *University of Glasgow (United Kingdom)*
Quantum-assisted adaptive optics for microscopy

Abstract:
It has been shown that imaging with entangled photons enable us to beat fundamental classical limits e.g. the shot-noise and the optical diffraction limit for resolution. However, quantum imaging schemes still suffer the same adverse effects due to optical aberrations that classical imaging does. In this respect, optical aberrations can quickly negate the performance benefits of imaging with entangled light. In our work, we show how to harness the spatial correlations inherent to spatially-entangled photon pairs sources to perform wavefront-sensorless adaptive optics and thus mitigate the aberrations. Adaptive optics (AO) is a broad field of methods to measure and correct for aberrations in an imaging system. Wavefront-sensorless AO finds this correction indirectly by optimising the quality of the images captured by the imaging system. This requires optimising some image quality metric. The choice of which metric to use may not be obvious but it can have large effect of the performance of the correction. We show that, by optimising directly on the photon-pairs spatial correlations, we are effectively directly optimising the point-spread function of the imaging system. This acts as a more robust and reliable metric, and is independent on the physical structure of the object being imaged. We also demonstrate that this method can enable defocus correction of an object with depth information, which is generally not possible with classical AO. Finally, we demonstrate that we can, in principle, perform high-order aberration correction with this method. Our work introduces a new concept of adaptive optics that exploits spatial correlations between entangled photon pairs. It could play an major role in the development of practical quantum microscopy systems.

Andrea Caprotti, *University of Vienna (Austria)*
Estimating local observables with snapshots of local Clifford unitaries

Abstract:
Verifying large entangled quantum systems represents one of the main challenges in employing such systems for real applications. Methods such as full-state tomography, which reconstruct completely the density matrix from measurements, require quantum resources that scale exponentially with the dimensions of the Hilbert space, making such approaches infeasible even at a medium scale. However, often the goal is to access only particular information about the quantum state, such as the mean values of certain observables of interest. New methods attempting to access only partial information about the system can significantly reduce the consumption of resources needed for estimation. A good example is the protocol of classical shadows (see: https://arxiv.org/abs/2002.08953), which utilizes the outcomes of randomized Clifford measurements to estimate the means value of an observable requiring a number of copies scaling as the Hilbert-Schmidt norm of the operator in question. For example, the cost scales as 2N for Pauli operators on N–qubits. While this scaling is optimal, the drawback is that quantum circuits of the size N^2 are needed to implement global Clifford measurements. Such demands are still far from what is available with the current technology. This work aims to investigate only local or low-depth Clifford measurements to extract useful information about a quantum system. By applying the classical-shadow protocol with l-local

Clifford measurements, we obtain bounds for the number of copies required to obtain expectation values of local observables. The analytical bound that has been obtained for the case Pauli (binary) observables show the sampling complexity of $(2l + 1)^{N/l}$, which for $l \to N$ corresponds precisely to the bound obtained for global measurements. Our result shows that significant estimation accuracy can be achieved even with moderate resources and low-depth quantum circuits, thus showing potential for applications in near-term quantum devices.

Silvia Cassina, *Università degli Studi dell'Insubria (Italy)*

Differential ghost imaging with speckled-speckle fields

Abstract:
The expression “super-thermal light” usually defines states of light characterized by intensity fluctuations higher than ones of thermal states.
This property makes it possible to observe intensity correlations when the optical states are correlated with themselves or with their replica at a beam splitter, thus rendering them particularly appealing for certain applications, such as for correlated imaging techniques. To this aim, in this work we exploit super-thermal states generated by a speckled-speckle field to implement ghost imaging protocols. Indeed, the autocorrelation function exhibited by super-thermal one is higher with respect to the case of thermal states of light, since the maximum value is equal to 4 instead of 2, while the normalized baseline is set to 2 instead of 1. The speckled-speckle field is obtained by impinging a laser beam on a sequence of two rotating ground-glass disks. The reported results are obtained from both simulated and experimental data, to allow comparison between expected and practical results. After a preliminary characterization of the generated light states in terms of autocorrelation function, we focus on the implementation of ghost imaging techniques, considering both standard ghost imaging and differential ghost imaging. In particular, a comparison between the results obtained exploiting thermal and super-thermal lights is performed considering some figures of merit, such as the contrast and the signal-to-noise ratio of the ghost images.
As a conclusion, it is evident both from simulations and experiments that the performance of differential ghost imaging increases using super-thermal light compared to thermal one.

Luis Octavio Castaños Cervantes, *Tecnológico de Monterrey (Mexico)*

Alternating measurement master equation and a quantum random-walk model

Abstract:
A master equation describing the evolution of the state of a quantum system subjected to alternating sets of measurements taking place at random times is deduced. The density operator of the system is expressed as the sum of two operators that satisfy coupled first order differential equations, each similar to the measurement master equation deduced in "Optics Communications 264 (2006) 352-361." The master equation can also be used to describe the evolution of the state of a system that has a fluctuating Hamiltonian or whose evolution between measurements can be described by GKLS equations (master equations in the Lindblad form). The results are applied to a quantum random-walk model on a one-dimensional lattice that switches randomly between two possibles states. The properties and long-time velocity and diffusion coefficient are analyzed and it is shown how the direction of the steady motion can be controlled.

Gabriele Cenedese, *Università degli Studi dell’Insubria (Italy)*
Efficient Generation of Highly Entangled States on Superconducting and Ion Trap Quantum Processors

Abstract:
One of the key requirements for quantum computers to achieve quantum advantage is the ability to generate a large amount of entanglement. In this poster, we propose a method to efficiently generate pseudo-random quantum states that exhibit nearly maximal multipartite entanglement.
We numerically demonstrate the optimality of our approach and use it to benchmark two different types of quantum processors: IBM's ibm_lagos superconducting qubit processor and IonQ's Harmony ion trap processor.
Our experimental results show that, despite the fact that ibm_lagos has lower error rates for single-qubit and two-qubit operations, Harmony outperforms ibm_lagos due to its low error rate in state preparation and measurement and its all-to-all qubit connectivity. This highlights the importance of qubit network architecture in generating highly entangled states.
Overall, our work demonstrates the potential of ion trap processors for quantum computation and provides a method for efficiently generating highly entangled states that could be useful for a variety of quantum algorithms and applications.

Carlo Cepollaro, *University of Vienna (Austria)*
Gravitational time dilation as a resource in quantum sensing

Abstract:
Atomic clock interferometers are a valuable tool to test the interface between quantum theory and gravity, in particular via the measurement of gravitational time dilation in the quantum regime. In the paper, we investigate whether gravitational time dilation may be also used as a resource in quantum information theory. In particular, we show that for a freely falling interferometer and for a Mach-Zehnder interferometer, the gravitational time dilation may enhance the precision in estimating the gravitational acceleration for long interferometric times. To this aim, the interferometric measurements should be performed on both the path and the clock degrees of freedom.

Abdelatif Chabane, *University of Abderahmene Mira Bejaia (Algeria)*
Non-Gaussianity for Harmonic Oscillator isospectral potentials

Abstract:
We address non-Gaussianity of quantum states of Harmonic Oscillator isospectral potentials introduced in the super-symmetric quantum mechanics approach (SUSYQM). Indeed, within this formalism, the non-uniqueness of the factorization has been exploited to generate one-parameter family of nonlinear potentials which are non-singular, exactly solvable, and strictly isospectral to the shifted harmonic oscillator potential (SHO). On the other hand, the generation, manipulation, and detection of non-Gaussian states have aroused growing interest in quantum optics, and quantum information. These quantum states are widely used in several protocols in quantum communication. After analyzing ground states and thermal states of some harmonic oscillator isospectral potentials, we evaluate the corresponding non-Gaussianity based on the quantum relative entropy (QRE) measure between the state under examination and a reference Gaussian state. We show explicitly that the studied states are non-Gaussian (Figure 1) and the non-Gaussianity feature is independent of the energy spectrum of the considered potential.

Grzegorz Chimczak, *Institute of Spintronics and Quantum Information, Faculty of Physics, Adam Mickiewicz University (Poland)*

Importance of passive PT-symmetry in quantum computing

Abstract:
The widespread use of quantum computers to solve problems unsolvable by classical computers is, unfortunately, still impossible. There is basically one obstacle - too high error rates of physical quantum gates. For example, current technology based on superconducting qubits makes it possible to perform quantum gates with an error rate of 0.001 [1]. Quantum error correction algorithms are very helpful, but without eliminating many physical sources of error, quantum computers will never reach their full potential.

Here, we consider a source of error that is common in open systems, i.e., loss of periodicity of the system [2]. All real systems are open systems, however, there are some open systems that behave like closed systems in terms of periodicity. These are open systems with passive PT symmetry. We show, on the example of quantum information transfer from quantum memory to the state of the electromagnetic field mode [3,4], that the use of passive PT-symmetric systems in the processing of quantum information allows to achieve fidelity values close to unity even in the presence of strong damping [2]. Finally, we generalize this conclusion to all real quantum information processing systems.

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Dario Alexande Chisholm, *Queen's University Belfast (United Kingdom)*

Quantum scrambling via accessible tripartite information

Abstract:
Quantum information scrambling (QIS), from the perspective of quantum information theory, is generally understood as local non-retrievability of information evolved through some dynamical process, and is often quantified via entropic quantities such as the tripartite information. We argue that this approach comes with a number of issues, in large part due to its reliance on quantum mutual informations, which do not faithfully quantify correlations directly retrievable via measurements, and in part due to the specific methodology used to compute tripartite informations of the studied dynamics. We show that these issues can be overcome by using accessible mutual informations, defining corresponding ``accessible tripartite informations'', and provide explicit examples of dynamics whose scrambling properties are not properly quantified by the standard tripartite information. Our results lay the groundwork for a more profound understanding of what QIS represents, and reveal a number of promising, as of yet unexplored, venues for futher research.

Alessandro Ciani, *Forschungszentrum Jülich (Germany)*
Quantum error mitigation for GKP qubits

Abstract:
In recent years, a plethora of quantum error mitigation techniques have been proposed to undo errors in currently available quantum devices. While these techniques are not a substitute for a fault-tolerant quantum computer as they are ultimately unscalable in the general case, they are still believed to play an important role for intermediate-scale devices. Most of these techniques have been developed for the case of qubits, while little work has been done for other quantum systems such as continuous variable systems. Recent works have also explored the application of error mitigation techniques together with error correction [1, 2, 3]. In this talk, we extend these ideas to the continuous variable case and, in particular, to the Gottesman-Kitaev-Preskill (GKP) code [4]. Focusing mostly on the technique of probabilistic error cancellation via quasiprobability decompositions, we show how to obtain such decompositions in the continuous-variable case in order to undo noise algorithmically in the quantum state, considering both ideal and finite squeezing GKP states. We also discuss how practically one could obtain the decompositions in an actual experimental setup without necessarily knowing the noise model in advance. The hardware efficiency of continuous variable codes makes it a perfect platform for testing the combination of error correction and error mitigation.

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Sebastiano Corli, *Politecnico di Milano (Italy)*
An alternative algebraic representation for graph states in measurement-based quantum computing

Abstract:
Graph states are the main computational building blocks of measurement-based computation and a useful tool for error correction in the gate model architecture. The graph states form a class of quantum states which are eigenvectors for the abelian group of stabilizer operators. They own topological properties, arising from their graph structure, including the presence of highly connected nodes, called hubs. Starting from hub nodes, we demonstrate how to efficiently express a graph state through the generators of the stabilizer group. We provide examples by expressing the ring and the star topology, for which the number of stabilizers reduces from n to ⌈ n 2 ⌉, and from n to 1, respectively. We demonstrate that the graph states can be generated by a subgroup of the stabilizer group. Therefore, we provide an algebraic framework to manipulate the graph states with a reduced number of stabilizers.

Baptiste Courme, *Sorbonne Université Laboratoire Kastler Brossel (France)*

Manipulation and certification of high-dimensional spatial entanglement in scattering media

Abstract:
High-dimensional entangled quantum states improve the performance of quantum technologies compared to qubit-based approaches. In particular, they enable quantum communications with higher information capacities or enhanced imaging protocols. However, the presence of optical disorder such as atmospheric turbulence or biological tissue perturb quantum state propagation and hinder their practical use. In this work, we demonstrate a wavefront shaping approach to transmit high-dimensional spatially entangled photon pairs through scattering media. Using a transmission matrix approach, we perform wavefront correction in the classical domain using an intense classical beam as a beacon to compensate for the disturbances suffered by a co propagating beam of entangled photons. Through violation of an Einstein-Podolski-Rosen criterion, we show the presence of entanglement after the medium. Furthermore, we certify an entanglement dimensionality of 17. This work paves the way towards manipulation and transport of entanglement through scattering media, with potential applications in quantum microscopy and quantum key distribution.

Marianna D'Amato, *Sorbonne Université Laboratoire Kastler Brossel (France)*

Towards a high-brightness and efficient integrated single photon source based on a perovskite nanocrystal coupled to an optical nanofiber

Abstract:
Quantum photonics and quantum information science's applications require on-demand single photon sources with high brightness and short lifetimes. Various materials systems have been investigated as candidates for single photon emission, such as single atoms and ions, but also solid-state emitters such as organic molecules, color centers in diamonds and quantum dots.

Among them, colloidal lead halide perovskites nanocrystals (NCs) have demonstrated high brightness, easy fabrication, and compatibility to room temperature operation. The main drawback of these emitters is their poor photostability under light illumination and dilution. I will present a study of Zn-doped CsZnPbBr3 perovskite nanocrystals showing increased photostability, reduced blinking together with a strong photon antibunching, which makes them very appealing as quantum emitters.

The integration of perovskite NCs with photonic interfaces, such as waveguides and optical fibers, represents a significant challenge in boosting their practical applications. We achieved for the first time the coupling of a single perovskite nanocube with a tapered optical nanofiber. Through near-field interaction, a significant fraction of the emitted light is coupled into the nanofiber and propagates to its end, providing proof of principle for a compact and integrated single photon source.

To further enhance the NC's emission properties and increase the collection efficiency of emitted single photons, various nanostructures can be introduced in the NC's photonic environment which can modify the local density of states (LDOS) and reduce the spontaneous emission lifetime via the Purcell effect. In this perspective, we explored a bottom-up fabrication method based on Electron Beam Induced Deposition (EBID), used here for the first time for directly fabricating plasmonic nano-antennas on a tapered optical nanofiber with deterministic and precise control on the material, location and geometry of the nanostructure. The successful implementation of this technique offers a promising perspective for the realization of a compact, efficient and high-brightness integrated single photon device.

Anita Dabrowska, *University of Gdańsk (Poland)*

Stochastic approach for evolution of a quantum system interacting with environment in squeezed number state

Abstract:
We determine filtering and master equations for a quantum system interacting with wave packet of light in a continuous-mode squeezed number state. We formulate the problem of conditional evolution of a quantum system making use of model of repeated interactions and measurements. In this approach the quantum system undergoes a sequence of interactions with an environment defined by a chain of harmonic oscillators. We assume that the environment is prepared in an entangled state being a discrete analogue of a continuous-mode number state. We present a derivation of a discrete stochastic dynamics that depends on the results of measurement performed on the field after its interaction with the system. In this paper we consider a photon counting measurement scheme. By taking a continuous time limit, we finally obtain differential stochastic equations for the system. Analytical formulae for quantum trajectories and exclusive probability densities that allow to fully characterize the statistics of photons in the output field are given.

Wang Dawei, *Dalian University of Technology (China)*

Simulating the extended Su-Schrieffer-Heeger model and transferring an entangled state based on a hybrid cavity-magnon array

Abstract:
Simulating the extended Su-Schrieffer-Heeger model and transferring an entangled state based on a hybrid cavity-magnon array
Dawei Wang
School of Physics, Dalian University of Technology, Dalian 116024, China

Taking advantage of the coherent coupling of magnons with different types of quantum systems, hybrid magnon systems have attracted much attention in recent years. In this work, we propose a scheme to simulate the extended Su-Schrieffer-Heeger (SSH) model by using the hybrid cavity magnonics system. We consider a hybrid cavity magnon array with N sites, where each site contains two cavity modes and one magnon mode, and the cavity modes at the neighboring site couple to each other with controllable tunneling rates. Under large detuning conditions, we adiabatically eliminate the cavity field and obtain periodic interactions between the magnons depending on the phase between adjacent cavity fields. After setting the relationship of the phases, we obtain the magnon version of the extended SSH model. Employing this model, we investigate the distribution of edge states and the topological phase transition. Moreover, our scheme can be easily extended to the SSHm model with the jump period m by setting different phase shifts. Finally, considering the non-integer cell case, we find that an arbitrary magnon entangled state can be encoded by two edge states and transferred from the left side end to the right site end via the adiabatic channel. Our work provides a new pathway for realizing quantum information transmission and offers an idea for implementing quantum simulations based on cavity magnonics systems.

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Serge Deside, *Université Libre de Bruxelles (Belgium)*
Probabilistic pure state conversion on the majorization lattice

Abstract:
We show that the majorization lattice provides the appropriate framework in order to characterize the allowed transformations of pure entangled states under local operations and classical communication. The underlying notions of meet $\wedge$ and join $\vee$ in the majorization lattice lead us to define, respectively, the optimal common resource and optimal common product states. Based on these two states, we introduce two optimal probabilistic protocols for the (single-copy) conversion of incomparable bipartite pure states, which we name greedy and thrifty. Both protocols reduce to Vidal's protocol [G. Vidal, Phys. Rev. Lett. 83, 1046 (1999)] if the initial and final states are comparable, but otherwise the thrifty protocol can be shown to be superior to the greedy protocol as it yields a more entangled residual state when it fails (they both yield the same entangled state with the same optimal probability when they succeed). Finally, we consider the generalization of these protocols to entanglement transformations involving multiple possible initial or final states.

Klaudia Dilcher, *University of Warsaw (Poland)*
Atomic magnetometry with Kalman Filters

Abstract:
Information inference from noisy systems is a focus of interest of various research and engineering disciplines. In 1960, Rudolf E. Kalman published a paper on an optimal filtering technique for systems described by linear dynamics and measurement models whose noise statistics is Gaussian [1]. In particular, this so-called Kalman Filter constitutes a way to construct an estimator that allows one to optimally extract the signal encoded in the system dynamics by minimizing the average mean-squared-error, despite the dynamics and measurement all undergoing uncontrolled independent stochastic fluctuations. In contrast to previously known algorithms, Kalman Filters do not require a full history of all previous computational steps, and so this technique is suitable for real-time data analysis and has proven to be very successful in many applications, including navigation systems, robotics, image processing and many more.

In this work, we applied Kalman Filters for magnetic field inference from an atomic sensor with optical read-out.
Such sensors are widely used in magnetometry both within and beyond the classical limit, achieving precision comparable to cryogenic methods. The Linear Kalman Filter has been applied to such systems before [2, 3], however the usability of this technique is very limited though, as the magnetic field obeys highly non-linear dynamics in most regimes. This suggests that using the Extended Kalman Filter can greatly improve the estimator beyond the linear regime. In this work, we simulate, for relevant experimental parameters, an output of such a sensor and show that in fact the magnetic field can be successfully estimated in real-time with the Extended Kalman Filter. We benchmark the results with those of other state-of-the-art frequency inference techniques.

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Gábor Drótos, *Institute for Nuclear Research (Hungary)*

Self-testing semi-symmetric informationally complete positive operator-valued measures in a prepare-and-measure scenario

Abstract:
Self-testing is the most powerful form of certification for quantum systems. In this work, we provide a method for self-testing the members of a one-parameter family of nonprojective qubit measurements. To this end, we adopt the construction of Tavakoli et al. [Sci. Adv. 6, eaaw6664 (2020)] who consider a prepare-and-measure (PM) scenario and assume a two-dimensional bound on the Hilbert space. We find that a simple PM scenario, one that involves four preparations and four measurements, is sufficient for self-testing, as the fourth measurement, the mentioned nonprojective qubit measurement, which is a four-outcome nonprojective positive operator-valued measure (POVM). In particular, it is a so-called semi-symmetric informationally complete POVM, introduced by Geng et al. [Phys. Rev. Lett. 126, 100401 (2021)]. Our analytical method for self-testing such measurements can pave the way for self-testing any extremal qubit POVM in a potentially minimal PM scenario.

Latifeh Eiri, *Friedrich Schiller University Jena, Institute of Physical Chemistry (Germany)*

Quantum oscillations in the photon statistics of two cavity fields

Abstract:
We present in this work a method to generate quantum oscillations in the photon statistics of two modes in a cavity. Within our model, these two modes interact with a three-level V-type atom and initialize transitions on two different pathways, namely from the ground state to either the first or the second excited state of the atom. Furthermore, we treat the two modes within second quantization and initialize these fields as coherent states.
It is well known that for such systems quantum collapses and revivals occur for the populations of the three levels. We can reproduce these effects if we choose the same coupling strength for both transition pathways and both modes. As a contrast to these larger temporal changes of the populations, only small changes can be observed in the photon statistics of the two modes as time advances.
Furthermore, we get a new oscillatory effect if we set the coupling strength for the first of the two transition pathways and the second of the two modes to zero. So, the first transition pathway interacts with the first mode only and the second transition pathway interacts with both modes. Then, the quantum collapses and revivals for the populations of the three levels appear again – but for the populations of the two excited levels an additional, slow oscillation appears.
Even more remarkable effects occur for the photon statistics of the two modes:
We see for the photon statistics for both modes a pronounced oscillation. In this oscillation, over time, the expected value for the number of photons in the first mode nearly doubles and then returns to its original value while the corresponding expected value for the second mode first decreases to near zero and then increases back to its original state. Thus, we observe a shifting of photons between the modes within our model.

To summarize, our finding illustrates that changing the strength of how atoms and cavity fields interact is crucial for controlling their complex interplay. This makes a significant contribution to the field of quantum optics, emphasizing the importance of adjusting coupling constants in cavity quantum electrodynamics. In particular, we found that if we set one coupling parameter to zero, we see an oscillation in the photon statistics of the two modes.

Davide Ferracin, *Università degli Studi di Milano (Italy)*
Universal Markovian Closure for Structured Fermionic Environments

Abstract:
Chain-mapping techniques are useful for trasforming a structured environment into a linear system, which can then be managed by well-known simulation algorithms relying on matrix-product states.
The transformed system is however still, theoretically, infinite in size, and the required simulation time and resources are usually very high in practice.
Nüßeler et al. (Phys. Rev. Lett. 129, 140604) developed a truncation scheme where (part of) the infinite linear environment is replaced by a small set of damped modes, the “Markovian closure”, which captures the dissipative dynamics of the environment and allows us to reduce the system to a finite size that is, most importantly, independent of the simulation time.
Our work consists in extending this closure scheme, which was up to now developed for bosonic environments, also to fermionic systems, obtaining a technique than can be used to simulate the evolution of quantum many-body or open systems such as the single-impurity Anderson model, in a way that is more resource-efficient than the standard chain mapping.

Massimo Frigerio, *Università degli Studi di Milano (Italy)*
Swift chiral quantum walks

Abstract:
We present a class chiral quantum walks on a broad variety of graphs solving the issue of sedentarity that burdens the evolution of many continuous-time quantum walks with real generators. By tuning the phase-parameters in the Hamiltonian, we show that the evolution of the walker starting from a highly connected vertex reaches the shortest quantum speed limit with respect to all the Hamiltonians compatible with the graph topology.

Bence Gábor, *Wigner Research Centre for Physics (Hungary)*
Ground-state bistability of cold atoms in a cavity

Abstract:
We experimentally demonstrate an optical bistability between two hyperfine ground states of trapped, cold atoms, using a single mode of an optical resonator in the collective strong coupling regime. Whereas in the familiar case, the bistable region is created through atomic saturation, we report an effect between states of high quantum purity, which is essential for future information storage. The source of nonlinearity is a cavity-assisted pumping between ground states of the atoms and the stability depends on the intensity of two driving lasers. We interpret the phenomenon in terms of the recent paradigm of first-order, driven-dissipative phase transitions, where the transmitted and driving fields are understood as the order and control parameters, respectively. A semiclassical mean-field theory is invoked to describe the nontrivial two-dimensional phase diagram arising from the competition of the two drive. The saturation-induced bistability is recovered for infinite drive in one of the controls. The order of the transition is confirmed experimentally by hysteresis in the order parameter when either of the two control parameters is swept repeatedly across the bistability region.

Félix Garreau de Loubresse, *Sorbonne Université Laboratoire Kastler Brossel (France)*

Combining a quantum cryptographic protocol with a high-efficiency quantum memory

Abstract:
An important step for quantum network development is to demonstrate cryptographic primitives combined with quantum memories. In this work, we combine a highly-efficient cold-atom-based quantum memory with the so-called quantum money protocol [1].

The purpose of this protocol is to secure transactions between a bank, a client and a vendor. The bank encodes a secret classical key into a sequence of qubits and the key contains the chosen polarization basis to prepare the qubits. These weak coherent states are stored into a quantum memory (i.e "credit card"), which is accessible to the client. By performing a transaction, the coherent states are retrieved from the memory and are measured by the vendor in a specific polarization basis. The measurement results and the choice of basis made are then sent to the bank which compares them with the secret key. Therefore, the communication error rate allows the bank to determine the trustability of the client and if the transaction can be validated or not. While other protocols such as quantum key distribution are well advanced, quantum money has not yet seen the same experimental progress, owing to the difficulty in implementing efficient enough quantum storage devices to beat the security threshold which is highly sensitive to errors and losses [2].

The quantum memory is based on ensemble of cold cesium atom and electromagnetically induced transparency [3]. Recently, we have reached storage-and-retrieval efficiency of 87% (±5%) on the D1 line of cesium in the single excitation regime, while preserving the entanglement of the stored quantum state [4]. In this context, our high efficiency and low noise memory platform allows to implement such protocol. We experimentally realized and validated the quantum money protocol with a memory layer. We benchmarked the main sources of noise contributing to the resulting error rate and demonstrated that the security threshold can be beaten.

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Davide Giannella, *INFN Sezione di Bari (Italy)*

Light-field imaging through position-momentum correlations

Abstract:
Correlation Plenoptic Imaging (CPI) is a well explored optical technique able to collect the light-field of a three-dimensional sample, namely the simultaneous knowledge of spatial information about its details and angular information about the direction of propagation of the light rays. This combined content is retrieved exploiting correlations intrinsic in the fluctuations of chaotic light and allows an enhancement of the natural depth-of-field, leading to the refocusing of out-of-focus planes of the imaged object and its three-dimensional reconstruction via stacking, in a single scanning-free acquisition, while keeping the resolution at the diffraction limit.
Depending on the way in which correlations are measured and the light-field retrieved, different protocols of CPI can be explored, in particular in the microscopy domain where the scheme named Correlation Light-

Field Microscopy (CLM) has recently been experimentally tested on simple test targets and biological volumetric phantoms, demonstrating the three-dimensional reconstruction capability of the technique intrinsic in the multi-perspective acquisitions, and its advantages in the depth-of-field extension with respect to conventional microscopy.
Along this line, an interesting new modality to perform correlation plenoptic imaging has recently been proposed. It consists in measuring position-momentum correlations performing the angular measurements directly in the Fourier plane of the imaging device, for example the back focal plane of the first lens of a two-lenses system (or of the objective of a microscope): in this scheme information of the at-focus plane is correlated with the one acquired directly imaging the Fourier plane.
We demonstrate how this operation contains plenoptic information, simulating a two-lenses setup and showing its capability of refocusing an out-of-focus binary mask.
A further advantage of this CPI scheme is the novel possibility to have direct access to the modal content of the sample: we show simulations on how this can be exploited to perform selection on illumination and object modes and how this enables entirely software spatial filtering by means of correlations.

Piotr Gładysz, *Nicolaus Copernicus University (Poland)*
Nonlinear behavior of Rabi frequency in polar systems

Abstract:
The topic is a two-level model where the quantum system is reduced to only two energy levels. Its optical properties are determined by spatial symmetries, quantified in terms of multipolar transition moments. Driving the system with a resonant plane wave causes a periodic transfer of population between the levels. The effect is known as Rabi oscillations, whose frequency depends, in the simplest case, on the amplitude of the driving field and the transition dipole moment of the quantum system.

This paradigmatic quantum optical effect is, however, hardly ever analyzed in polar systems, in which the broken inversion symmetry induces new effects. Polar systems support permanent dipole moments that can be different in the ground and excited eigenstates. Hence, the transitions of the population give rise to an additional oscillating dipole that is a source of radiation at the Rabi frequency. This frequency can be controlled within the MHz to even THz regime, giving rise to all-optically tunable coherent radiation sources exploiting the polar nature of quantum systems.

However, the existence of the permanent dipole moments also affects the Rabi frequency itself. The Rabi frequency of non-polar systems scales linearly with the amplitude of the driving electric field. For highly polar systems subject to relatively strong fields this scaling is modified. Our preliminary studies suggest field intensity regimes where the Rabi oscillations' frequency is robust and field-independent, as well as regimes where the frequency collapses back to near-zero values at strong fields. The robust character may enable coherent response of atomic ensembles subject to strong fields rapidly varying in space – the conditions characteristic to the vicinity of plasmonic nanoparticles. The collapse back to the linear regime around the near-zero Rabi frequency values, on the other hand, may be exploited for precise strong-field metrology.

Alfred Godley, *University of Nottingham (United Kingdom)*

Optimal estimation of quantum Markov chains using adaptive measurements

Abstract:
Quantum metrology aims to estimate parameters from a family of quantum states. Quantum open systems provides an interesting setting for metrology as we can estimate the parameters by monitering the environment instead of measuring the system directly. However, determining the optimal measurements to make is a difficult problem.
In this poster we present recent work estimating a single parameter in the setting of a discrete-time quantum Markov chain. We utilize an additionally system, known as the absorber, to post processes the output. Then, by implementing an adaptive measurement algorithm that depends on the previous measurement results, we can achieve the optimal estimation bound. This is confirmed through numerical studies.

DOI: https://doi.org/10.22331/q-2023-04-06-973

Jan Gulla, *University of Oslo (Norway)*

Limits for realizing single photons

Abstract:
Single photons are infinitely spread out in space and time, meaning that they cannot be generated on demand (i.e., produced by a local trigger without any postselection). In contrast, optical states that are distinguishable from vacuum only inside some region are said to be strictly localized. These states are possible to generate on demand, with the best-known example being the coherent states. However, coherent states are very different from single photons, which leads to the question: how close can an optical state generated on demand be to a single photon?

We answer this question for the first time (https://arxiv.org/abs/2109.06472). To quantify how close realizable states can be to some target single photon, we argue that there are two natural but incompatible ways to specify the target state. Either it can be expressed as a photon with a chosen, positive-frequency spectrum, or it can be described as an (unphysical) photon in a chosen, positive-time pulse. We determine upper and lower bounds for the maximum fidelity in both cases. The bounds are expressed as a function of the size of the target state's tail.

Our results have important implications for the future of quantum-optical devices. The maximum fidelity turns out to depend on the shape of the desired target pulse: For ultrashort pulses or pulses with rapidly varying envelopes, the theoretical maximum single-photon fidelity is significantly less than one. This means that as photon sources continue to improve and approach pulse lengths of a single optical cycle, the generated pulse must necessarily contain substantial multiphoton components. On the other hand, as the pulse envelope becomes more slowly varying compared to an optical cycle, the optimal fidelity increases rapidly. In addition, our analysis allows a manifestly causal description of propagating signals in quantum field theory, potentially opening up new methods for describing such processes.

Malte Hagemann, *University of Hamburg (Germany)*

A 10-dB squeeze laser tunable over half a nanometre around 1550 nm

Abstract:
Tunable lasers have a wide application in spectroscopy. We have developed a squeezed laser that generates 10-dB squeezed vacuum states at a central wavelength of 1550 nm while being tunable by 0.5 nm. The squeezed states were generated by parametric amplification in a periodically poled potassium titanyl phosphate crystal in a standing-wave resonator. We achieve squeeze values of at least 10.5±0.1 dB in a range from 1549.9 nm to 1550.34 nm with a maximum of 11.0±0.1 dB at a 775-nm pump power of about 15 mW.
The fine tuning of the phase matching in the crystal as well as at the crystal ends is achieved via local temperature settings. For our example crystal, the improved adjustment possibility of the phase matching caused a reduction of the required pump power by 4%. The wavelength range is currently limited by the tunability of the 1550-nm master laser. Our approach is transferable to other wavelength ranges.

Danish Hamza, *Institute of Theoretical Physics, University of Warsaw (Poland)*

Unveiling the Structure of Many-Body Quantum Correlations in Spin Chains

Abstract:
We presents an investigation of the intricacies of many-body entanglement and non-locality in spin chains. By utilizing a hierarchical analysis of many-body correlations, we gain a deep understanding of the structure of a underlying quantum state. We apply this technique to well-known systems such as the Ising chain, showcasing its potential for ultra-precise metrology and quantum technology applications. Our results contribute to the fundamental understanding of many-body quantum systems.

Fumiya Hanamura, *University of Tokyo (Japan)*

Efficient implementation of multi-mode non-Gaussian gates using nonlinear feedforward

Abstract:
Optical continuous-variable(CV) quantum computation is a promising platform for large-scale universal quantum computation. In addition to the large-scale Gaussian operations enabled by the cluster state [1], at least one non-Gaussian gate is needed for the universal quantum computation. An efficient implementation of a single-mode cubic phase gate (x^3, CPG) using a non-Gaussian ancillary state and nonlinear feedforward has been proposed [2] and partially has been implemented in experiments [3]. Although in principle universal quantum computation is possible with only single-mode CPGs and multi-mode Gaussian operations, multi-mode non-Gaussian gates such as cubic-QND gate (x_1 x_2^2) and Toffoli gate (x_1 x_2 x_3) are more suitable for practical applications [4]. Cubic-QND gate is useful for important tasks in quantum computation such as GKP state preparation and realization of Rabi-type interaction [4]. Toffoli gate is a quantum version of AND gate and forms a universal gate set together with a Hadamard gate [5]. Several methods have been proposed to realize these gates, including decomposition into multiple CPGs and beamsplitters [4], and a gate teleportation method which requires online squeezing operations [6]. However, these methods have not been optimized in terms of resources and experimental feasibility.

In this work, we extend the simplification method used for the CPG [2] to multi-mode cases. Our method consists of multi-mode non-Gaussian ancillary state, passive beamsplitters, and nonlinear feedforwards to the phases of homodyne measurements and the transmittance of variable beamsplitters. Our method does not require online squeezing operations, and reduces the number of beamsplitters and ancillary modes compared to previous proposals [4,6]. This result accelerates the progress toward the experimental realization of universal quantum computation.

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Dmitri Horoshko, *Université de Lille (France)*
Time-to-Space Ghost Imaging with Classical and Quantum Light

Abstract:
In temporal ghost imaging (TGI) the image of a temporal object is formed by detecting two temporally correlated beams: the test beam passing through the object is detected by a single-temporal-pixel detector, while the reference beam is detected by a fast detector. TGI and its spatial counterpart attract much attention since they are inherently insensitive to the distortion that may occur between the object and the single-pixel detector, allowing one to form high-resolution images in a strongly scattering medium. The temporal resolution of TGI is determined by the response time of the fast detector and its best value reported is 55 ps [1]. To improve the temporal resolution, we propose to form a spatial ghost image of a temporal object relying on strong temporal-spatial correlations between the test and reference beams.

First, we consider temporal-spatial correlations between two entangled beams generated in type-I parametric downconversion (PDC) [2]. We propose to select a spectro-angular band where the transverse wave vector of the reference photon depends linearly on its frequency detuning from the PDC central frequency. This photon is detected in the far field by a camera. Its twin is collimated into a single-mode fibre and propagates through a frequency-to-time mapping system, then through a point temporal object, after which it is detected by a single-pixel detector. We calculate analytically and numerically the correlation function C(x1,t2) between the time of passage of the test photon through the temporal object t2 and the detected position of the reference photon x1. This function demonstrates the possibility to form a ghost image with a resolution about 500 fs, two orders of magnitude better than in the conventional TGI [3].

Second, we consider a classical source of partially coherent light with correlations described by a spatiotemporal Gauss-Shell model and show that they can also be used for realizing a time-to-space ghost imaging, but with a lower contrast, compared to the quantum source.

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Sheng-Hsuan Huang, *Max Planck Institute for the Science of Light (Germany)*
Polarization-entangled photons from whispering gallery resonators

Abstract:
Crystalline Whispering Gallery Mode Resonators (WGMRs) have a lot of interesting features, such as high Q factor, low volume value, and tunable coupling rate. It has been shown that WGMRs made from chi^2 nonlinear materials can be compact and efficient sources of quantum states, e.g. squeezed states or heralded single photons. It has also been shown that the generated photons can interact with atom systems efficiently due to the narrow and tunable bandwidth of the generated photons. These features make WGMRs

a versatile platform for quantum information processing. However, there is one key aspect missing: neither frequency entanglement nor polarization entanglement has been implemented in WGMRs yet.
In our experiment, we use a WGMR fabricated from z-cut MgO-doped lithium niobate and use type-I phasematched SPDC process to generate the quantum states. By coupling two beams propagating in opposite directions, that is in the clockwise direction (CW) and the counterclockwise direction (CCW), into the resonator at the same time, we can use identical phase matching conditions in both travelling directions, which make the CW and CCW beams in an ideal case indistinguishable. By sending these in Mach-Zehnder interferometers, we use the generated photons to create polarization-entangled states. As with most interferometric schemes, the exact entangled state is governed by the relative phase between the two sources. We demonstrate that we can control the produced entangled states by changing the entangled-states between the singlet state and the triplet state. Moreover, we demonstrate the non-local two photons interference by changing the polarization projections. The visibility of the result is 86% (89%, 89%, 95%) on A (D, V, H) basis. All the values are higher than the classical limit 71%, indicating a true quantum interference phenomenon in the fourth-order of the electric field. Last but not least, we extract the S value from the measurements. The S value is 2.45pm0.07, which violates the CHSH inequality by more than 6 standard deviations. This is, to the best of our knowledge, the first time that polarization-entangled photons has be shown from WGMRs.

Florian Huber, *Ludwig Maximilian University of Munich (Germany)*

Bohmian Trajectories of Quantum Walks

Abstract:
Standard quantum mechanics famously disallows to simultaneously measure a particle's position and momentum with arbitrary precision. In contrast, Bohmian mechanics, a hidden-variable interpretation of quantum mechanics, at the same time ascribes reality to the positions and momenta of quantum particles at the cost of a non-local ontology. It thus allows to reconstruct definite particle trajectories, while being fully compatible with the standard theory in all empirical predictions. In case of photons, Bohmian trajectories correspond to energy flow lines derived from classical electrodynamics, which follow the Poynting vectors.

Here we report on the simulation and first measurements of energy flow lines of a quantum random walk, realized in an integrated waveguide array written into fused silica substrate by femtosecond laser writing. The waveguide array consists of five waveguides which are in close proximity to each other in order to allow evanescent coupling.

To reconstruct these energy flow lines in an experiment, we magnify the spacial distribution of the photons leaving the waveguide array with a phase front preserving optics and afterwards measure the Poynting vectors by a weak coupling between the transverse momentum of the photon and its polarization followed by a strong spatially resolving polarization measurement. Due to the weak coupling the photons transversal momentum is proportional to the change of the expectation value of the polarization. Thus the final strong polarization measurement yields the desired information about the Poynting vectors.

The evolution time of the quantum random walk can be adjusted by varying the length of the waveguide array or by changing the coupling strength. This way we trace the energy flow, i.e. the path of the photons, of a quantum random walk in an integrated waveguide structure.

Aurelian Isar, *National Institute of Physics and Nuclear Engineering (Romania)*
Entropy production and quantum correlations in two coupled bosonic modes interacting with a thermal environment

Abstract:
The Markovian time evolution of the entropy production rate as an indicator of the irreversibility, in comparison with the correlations like Rényi-2 mutual information, Rényi-2 quantum discord and entanglement is studied, in a bipartite quantum system consisting of two coupled bosonic modes embedded in a common thermal environment. The dynamics of the system is described in the framework of the theory of open systems based on completely positive quantum dynamical semigroups, for initial two-mode squeezed thermal states, squeezed vacuum states and coherent states. We show that the rate of the entropy production and the considered correlations in the non-equilibrium stationary state, as well as the time evolution of the rate of entropy production and of the correlations, strongly depend on the parameters of the initial Gaussian state (squeezing
parameter and average thermal photon numbers), frequencies of the modes, the parameters characterising the thermal reservoir (temperature and dissipation rate) and thecoupling between the two bosonic modes [1,2].

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Kabgyun Jeong, *Seoul National University (Republic of Korea)*
Quantum Rényi Entropy Functionals for Bosonic Gaussian Systems

Abstract:
In this study, the quantum R'{e}nyi entropy power inequality of order $p>1$ and power $kappa$ is suggested as a quantum analog of the classical R'{e}nyi-p entropy power inequality. To derive this inequality, we first exploit the Wehrl-p entropy power inequality on bosonic Gaussian systems via the mixing operation of quantum convolution, which is a generalized beamsplitter operation. This observation directly provides a quantum R'{e}nyi-p entropy power inequality over a quasi-probability distribution for D-mode bosonic Gaussian regimes. The proposed inequality is expected to be useful for the nontrivial computing of quantum channel capacities, particularly universal upper bounds on bosonic Gaussian quantum channels.

Kateřina Jiráková, *Palacký University (Czech Republic)*
Hierarchy of quantum correlations of experimentally prepared Werner-like states

Abstract:
Experimental Bell states of high quality are a vital resource for quantum communication. Unavoidably, though, they experience decoherence effects resulting in the decrease or deterioration of entanglement and also the possible presence of noise in the communication channel. It is of practical importance to investigate hierarchy of the following classes of quantum correlations: separability, entanglement, steering in two- and three-measurement scenarios, and Bell nonlocality. Such a study is presented in Jiráková et al. PRA 104 (2021) where the authors have experimentally generated Werner states, which are white-noise-affected Bell states. Werner states are, thus, prototypal examples for studying such a hierarchy as a function of the amount of white noise.
The authors also prepared generalisations of Werner states, i.e., partially entangled pure states affected by white noise. Such states have, two tunable parameters, one controls the amount of added white noise and the second one, denoted as q, influences the entanglement of the pure state. Partially entangled states find

their application in quantum cryptography in quantum key distribution and for dense coding. Interestingly, these generalised Werner states (GWSs) feature different hierarchy of correlations with respect to Werner states. Specifically, they are steerable in the 2-measurement scenario but do not violate the Bell inequality so they admit local hidden variable model. This regime cannot be observed for the usual Werner states. Optimal parameter q has been found to define GWS that are more robust against white noise compared to Werner states. In other words, these states allow for the largest amount of white noise and yet they maintain their specific quantum correlations.
This observation could be applied in quantum cryptography. Consider that one communicating party wants to use, e.g., steering and not to be detected by other users by the violation of Bell inequalities. In this case, partially entangled states can be used for quantum communication by means of a depolarising channel.

Dominick Joch, *Griffith University (Australia)*

Certified random-number generation from quantum steering

Abstract:
The certification of the randomness of number sequences has remained a long-standing difficulty for almost a century. Truly random numbers are an essential resource for cryptography and numerous other applications, but typically rely on statistical tests of the sequences that reveal nothing about the security of their generation and are thus insufficient as certification of genuine randomness. Indeed, such tests may be passed by pseudo random number generation (RNG), which is deterministic, yet most used despite being dependent on an adversary lacking the computing power to guess the seed.

Quantum phenomena possess intrinsic randomness, thus quantum-RNG (QRNG) presents itself as the most appealing avenue for secure randomness. Naïve approaches rely on strong assumptions about the physical devices, making them susceptible to adversarial exploitation via side information and device imperfections. However, by exploiting quantum nonlocality, one can devise QRNG schemes with device independence (DI), and the best possible levels of security. Full DI-QRNG is highly challenging experimentally, motivating partially-DI schemes with significant advantages in ease of implementation that can become commercially feasible sooner. Our work implements one such protocol–a certified random number generator based on the quantum steering nonlocality task–that is more robust to loss and noise compared to DI-QRNG protocols, allowing us to certify randomness below the efficiencies required for DI-QRNG while having superior security to trusted-device and many other partially-DI approaches.

Our implementation of the protocol employs a high-quality source of single photons and superconducting nanowire single photon detectors to demonstrate randomness expansion by meeting stringent efficiency and noise requirements. We create entangled photon pairs by spontaneous parametric downconversion (SPDC) to prepare states that have a high fidelity of 0.9933 ± 0.0005 with the maximally entangled singlet Bell state. The protocol was performed to acquire a
min-entropy certification of randomness, we then applied a quantum-proof randomness extractor to obtain the final certified random bit sequences. This steering-based approach allows for post-selection of trials, so the per-trial randomness can be significant compared to DI-QRNG with SPDC. Our scheme can be refined to serve as a viable randomness beacon and is an important step to bringing improved security to private randomness for cryptographic purposes and sources of public randomness.

Malo Joly, *Sorbonne Université Laboratoire Kastler Brossel (France)*
Photonic Quantum reservoir computing with wavefront shaping and multimode fiber

Abstract:
Machine Learning is omnipresent in today's technologies and the required computing power is ever-increasing. Recurrent Neural Networks (RNN) are powerful for handling evolving input but are notoriously hard to train. Reservoir computing is a RNN model where a network of weights are fixed and only a readout layer is trained. This computing paradigm is promising for physical implementations because it requires no (or few) nano-engeneering. Moreover, multimode fibers (MMF) with wavefront shaping have showed possibilities to process quantum information and implement quantum linear networks. Constructing on these two ideas, we propose a scalable experimental system to harness the power of reservoir computing with SPDC pairs of photons through a MM and measured on a SPAD, whose wave function is controlled with a spatial light modulator (SLM). We encode the input and reservoir state on the SLM and use the multimode fiber to couple the modes of the two-photon state and act as the reservoir weights. The SPAD detector then is able to measure coincidences between indistinguishable photons which are the output of the network. This proof of concept proposed experiment could be scaled to a higher number of indistinguishable photons and bigger SPAD arrays.

Adrian Juan-Delgado, *Centro de Fisica de Materiales (Spain)*
Tailoring the intensity correlation of light scattered from coupled organic molecules

Quantum technologies can benefit from the use of organic molecules at cryogenic temperatures because they have an extremely narrow zero-phonon line and are efficient single-photon sources. Additionally, when molecules are located at short separation distances, the dipole-dipole interaction between them gives raise to the emergence of superradiant and subradiant states, which can impact applications such as quantum information storage. In this context, the ability to experimentally manipulate the coherent interaction between pairs of organic molecules has been recently reported [1]. We present here a systematic theoretical analysis of the intensity correlation of light emitted from two coupled dibenzanthanthrene (DBATT) molecules and show that measuring this correlation can improve the experimental characterization of such interacting molecules.

We first investigate the standard color-blind intensity correlation (which considers all the photons arriving to the detectors) of light emitted from two coupled molecules. We demonstrate that this intensity correlation can be tailored on demand by changing the intensity and frequency of the laser that drives the molecules. For example, we find that under weak illumination the emission is strongly antibunched if the laser is tuned to the transition frequency of the superradiant state, which indicates that the system behaves as an efficient single-photon source. In contrast, if we tune the laser to the two-photon resonance the emission results strongly bunched under weak illumination. Moreover, we find a complex behavior of the intensity correlation when the laser is tuned to the transition frequency of the subradiant state, opening the possibility to emit both bunched and antibunched light, depending on the intensity of the illumination.

Additionally, we explore the frequency-resolved intensity correlation for the same two coupled organic molecules. This technique consists in measuring the correlation between pairs of photons of well-defined frequencies and provides additional information on the different emission mechanisms of the system. Interestingly, frequency-resolved correlations can unveil processes that remain hidden in the one-photon spectrum, such as two-photon transitions through virtual states. Moreover, we find that the frequency-resolved correlations can also unveil one-photon transitions which are hard to identify from the emission spectrum. These results stress the interest of the intensity correlations to better characterize and understand the emission from coupled molecular systems.

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Vojtech Kala, *Palacký University (Czech Republic)*
Nonlinear squeezing and its decoherence

Abstract:
Nonlinear squeezing is a feature of quantum non-Gaussian states that manifests as suppression of noise with respect to a nonlinear combination of quadrature operators. Quantum states with nonlinear squeezing are a resource for universal quantum computation and in principle enable universal control of a continuous variable system [1]. With the first experimental realization [2] and the ongoing discussion of possibilities of preparation [3] it is vital to understand how these states are influenced by experimental imperfections. In this contribution we show how the non-Gaussian properties of such states scale with decoherence and how can Gaussian operations be used to enhance their robustness [4].
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Mahmoud Kalash, *Max Planck Institute for the Science of Light (Germany)*
Wigner Function Tomography via Optical Parametric Amplification

Abstract:
Wigner function tomography is indispensable for characterizing quantum states, but its commonly used version, balanced homodyne detection, suffers from several weaknesses. First, it requires efficient detection, which is critical for measuring fragile non-Gaussian states, especially bright ones. Second, it needs a local oscillator, tailored to match the spatiotemporal properties of the state under test, and fails for multimode and broadband states. Here we propose Wigner function tomography based on optical parametric amplification followed by direct detection. The method is immune to detection inefficiency and loss, and suitable for broadband, spatially and temporally multimode quantum states. To prove the principle, we experimentally reconstruct the Wigner function of squeezed vacuum occupying a single mode of a strongly multimode state. We obtain a squeezing of -7.5 ± 0.4 dB and a purity of 0.91 ± 0.09 despite more than 97% loss caused mainly by filtering. Theoretically, we also consider the reconstruction of a squeezed single photon - a bright non-Gaussian state. Due to strong multimode parametric amplification, the method allows for the simultaneous tomography of multiple modes. This makes it a powerful tool for optical quantum information processing.

Marcin Karczewski, *University of Gdańsk (Poland)*
Heralded entanglement via photon subtractions

Abstract:
We present a method of generating entanglement exploiting the correlations between identical particles. It consists on applying a series of single-particle subtractions to a product state of photons. By properly tailoring these subtractions, one can design optical schemes producing a variety of entangled systems, including GHZ, W or graph states. Their generation is heralded, decentralized and relatively easily generalized to target states with more parties or levels. This work is based on [Phys. Rev. A 100, 033828] and [arXiv:2211.04042].

Ilya Karuseichyk, *Sorbonne Université Laboratoire Kastler Brossel (France)*

Estimating multiple parameters of point sources using spatial mode demultiplexing

Abstract:
The spatial mode demultiplexing technique (SPADE) for resolving point sources beyond the Raleigh limit gained considerable attention during the last few years. Although in the presence of detection noise and demultiplexing cross-talk this approach faces the so-called Raleigh curse, it allows for a significant reduction of the measurement statistics needed to estimate the separation of the source, compared to a direct imaging approach.

However, most studies on separation estimation have focused on single-parameter problems. They rely on assumptions such as equal and known brightness of sources and known positions of centroids. In this research, we use the method of moments to analyze the multiparameter estimation problem for two mutually coherent point sources. This allows us to remove part of the assumptions about our knowledge of the parameters and consider the general quantum statistics of the emitters. Our findings indicate that any potential advantage from the statistics' nonclassicality is wiped out by our ignorance of the sources' brightness [1]. We also examine the ratio of the sources' brightness and mutual phase as parameters, comparing the efficiency of SPADE to direct imaging. Even though the sensitivity of the separation estimation depends heavily on the mutual phase and relative intensity of the sources, we find that there is a simple linear estimator for the separation independent of these parameters and its sensitivity is close to optimal.

The same approach is also applicable for the analysis of multiple sources resolving, providing simple linear estimators for multiple parameters without the necessity to carry out heavy computations such as maximum likelihood estimation. These findings bring SPADE technique closer to practical applications, where one doesn't have prior information about the objects under study and has limited detection capabilities and computational power.

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Konstantin Katamadze, *Technology Innovation Institute (United Arab Emirates)*

Using spatial mode transformation and photon statistics to break Rayleigh's curse for multiparameter object imaging

Abstract:
According to the Rayleigh criterion, it is impossible to resolve two statistically independent point sources separated by a distance below the width of the point spread function (PSF). Almost twenty years ago it was shown that the distance between two point sources can be statistically estimated with an accuracy better than the PSF width. However, the estimation error increases with decreasing distance. This effect was informally named Rayleigh's curse. Next, it was demonstrated that PSF shaping allows breaking the curse provided that all other source parameters except for the distance, are known a priori. We propose an imaging technique based on the target Beam moduLation and the Examination of Shot Statistics (BLESS). Using both quantum and classical Fisher information approaches, we show that the technique can break Rayleigh's curse even for unbalanced point sources with unknown centroid and intensity ratio.

Mikhail Kolobov, *Université de Lille (France)*
Temporal Imaging for Making Entangled Photons Indistinguishable

Abstract:
Indistinguishability of photons occupies an important place in quantum information and communication theory. Having no classical counterpart, it plays a crucial role in linear optical quantum computation, boson sampling, and quantum sensing. One of the most perspective sources of single photons is type-II spontaneous parametric down-conversion with a pulsed broadband pump. It is known that in this case, the signal and the idler photons have in general different spectral and temporal properties [1]. This effect deteriorates their indistinguishability and the visibility of the Hong-Ou-Mandel interference, respectively.
We propose an application of quantum temporal imaging [2] to restoring the indistinguishability of the signal and the idler photons. We demonstrate that inserting a time lens in one arm of the interferometer and choosing properly its magnification factor restores perfect indistinguishability of the signal and the idler photons and provides 100% visibility of the Hong-Ou-Mandel interference in the limit of high focal group delay dispersion of the time lens [3].
In our calculations, we assumed a Gaussian shape of the pump pulses for the spontaneous parametric down-conversion source and also used a Gaussian approximation for the phase-mismatch function of the nonlinear crystal. These two conditions allowed us to obtain several important analytical results, for example, for the spectra of the ordinary and the extraordinary waves and also for the temporal shapes of the emitted pulses. We also obtained an analytical formula for the optimum value of the magnification factor of the time lens, which provides the unit visibility of the Hong-Ou-Mandel interference. We give a simple physical interpretation of this result in terms of the temporal durations of the ordinary and the extraordinary pulses.
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Denis Kopylov, *University of Paderborn (Germany)*
Simulations of Degenerate Parametric Down-Conversion in Lossy Waveguides

Abstract:
Denis A. Kopylov (1, 2), Polina R. Sharapova (1), Torsten Meier (1, 2)
1. Department of Physics, Paderborn University, Warburger Straße 100, Paderborn D-33098, Germany
2. Institute for Photonic Quantum Systems (PhoQS), Paderborn University, Warburger Straße 100, Paderborn D-33098, Germany

Nowadays, the most common sources of quantum light are based on spontaneous parametric processes. Here we focus on parametric down-conversion (PDC) which allows one to realize extremely flexible sources and, e.g.
prepare not only bi-photons and squeezed states, but also non-Gaussian light states using projection measurements (PRX Quantum 2, 030204 (2021)).
The development and design of waveguide-based PDC sources are especially relevant for quantum optical circuits which are promising tools for novel quantum technological applications.
In comparison to bulk crystals, where the absorption losses are small and can be neglected, long nonlinear waveguides typically possess surface roughness which leads to significant scattering losses for guided light (New J. Phys. 21, 033038 (2019)).
Therefore, PDC modes reveal losses present during their generation and the final PDC state will be mixed. In turn, the adequate understanding of the properties of states generated in lossy waveguides is crucial, especially when they are used in the technological applications, e.g., photonic quantum computing.

In this work, we theoretically investigate degenerate PDC in lossy waveguides.
Using the Heisenberg picture and the quantum Langevin equation, we performed both analytical and numerical solutions for the creation and annihilation operators of the generated light.
We show that scattering causes not only losses of the initial PDC modes, but also leads to the appearance of additional uncorrelated noisy photons.
Numerical simulations are performed both in the low- and high-gain regimes of PDC for parameters achievable in experiments.
We demonstrate how purity and minimal squeezing depend on the scattering losses.
In order to emphasize the importance of losses inside nonlinear waveguides we study Gaussian boson sampling (GBS) with a lossy PDC source and compare the obtained results with GBS based on an ideally squeezed state.

This work is supported by the "Photonic Quantum Computing" (PhoQC) project which is funded by the Ministry for Culture and Science of the State of North-Rhine Westphalia.

Marcin Koźbiał, *University of Warsaw (Poland)*

Spin-noise spectroscopy of alignment-based atomic magnetometers

Abstract:
Alignment-based optical magnetometers are capable of measuring magnetic fields with high accuracy. Their advantage is that they use only a single linearly polarised laser beam to both pump and probe the atomic ensemble [1]. However, the theoretical description of these magnetometers requires usage of more sophisticated mathematical tools. In contrast to atoms pumped with circularly polarised light (orientation-based magnetometers), each of which can be treated then as spin-1/2 object, atoms pumped with linearly polarised light effectively behave as spin-1 particles. As a result, one needs rank-2 spherical tensors to model dynamics of the magnetometer [2] and, in particular, abandon describing the atomic state with a three-component vector, but rather resort to the so-called spin alignment.

The purpose of spin-noise spectroscopy is to characterise the noise properties of a given atomic system [3] and, in particular, its stochastic nature. However, only in the case of orientation-based magnetometer noise models have been proposed and verified, see e.g. [4], while their generalisation to alignment-based magnetometers is still missing.

In our work, we employ methods of stochastic calculus and formalism of spherical tensors to predict the power spectrum of an alignment-based magnetometer in presence of a static magnetic field affected by perpendicular white noise. Our model predicts existence of peaks related to the Larmor frequency, and their dependence on the system geometry and the noise intensity. The model is verified in a series of experiments, whose results show good accordance with the predictions for noise amplitudes smaller and comparable to the intensity of the static field.

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Stanisław Kurdziałek, *University of Warsaw (Poland)*
Measurement Noise Susceptibility in Quantum Estimation

Abstract:
Fisher information is a key notion in the whole field of quantum metrology. It allows for a direct quantification of the maximal achievable precision of the estimation of the parameters encoded in quantum states using the most general quantum measurement. It fails, however, to quantify the robustness of quantum estimation schemes against measurement imperfections, which are always present in any practical implementations. In our work, we introduce a new concept of Fisher information measurement noise susceptibility (FI MENOS) that quantifies the potential loss of Fisher information due to small measurement disturbance. We derive an explicit formula for the quantity, and demonstrate its usefulness in the analysis of paradigmatic quantum estimation schemes, including interferometry and superresolution optical imaging.

POSTER SESSION 2, Thu 6th July 2023

Daniela Angulo Murcillo, *University of Toronto (Canada)*

How long do resonant photons spend as atomic excitations before being transmitted?

Abstract:
If a resonant photon traverses a medium and is transmitted to the far side, how much time does it spend as an atomic excitation? Previous work (PRX Quantum 3, 010314) demonstrated that transmitted photons excite atoms for nearly as much time as average photons do. Since that work was limited to measurements using only broadband pulses of light, it was not able to distinguish between several theoretical models that make strikingly different predictions in the case of excitation with narrowband pulses and media with low optical depth. In particular, the weak-value formalism suggests that this excitation time could be negative under such conditions. We present experimental progress to investigate this prediction and aim to further elucidate the history of resonant photons that are ultimately transmitted through a cold cloud of 85Rb atoms.

Anindita Bera, *Nicolaus Copernicus University (Poland)*

A class of optimal positive maps in matrix algebra M_n

Abstract:
I will discuss about a certain class of positive maps in the matrix algebra M_n consists of optimal maps, i.e. maps from which one cannot subtract any completely positive map without loosing positivity. This class provides a generalization of a seminal Choi positive map in M_3.

Árpád Kurkó, *Research Centre for Physics,* Budapest *(Hungary)*

Collection efficiency of radiation emitted by a trapped atomic ensemble

Abstract:
Trapped atomic ensembles are convenient systems for quantum information storage in the long-lived sublevels of the electronic ground state and its conversion to propagating optical photons via stimulated Raman processes. Large ensembles of atoms with Λ-configuration of levels is a promising tool for transducing microwave photons to optical photons. In this poster I am going to present two ways of the microwave to optical conversion: realized by cold atoms [1] and ultracold atoms [2] that form a degenerate quantum gas – Bose-Einstein condensate. I will show the similarities and the differences between these two realizations, and also the optimal conditions for the emitted optical photons to be collected into the guided modes of optical fibers.

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Theerthagiri Lakshmanan, *University of Camerino (Italy)*

Neyman Pearson target detection test for quantum illumination of a phase conjugate receiver

Abstract:
In quantum illumination, one photon from an entangled pair is sent in the direction of the target object while the other photon remains at the sender's location. The first photon engages with the object and undergoes a change in response to its presence and location. The sender can then use their knowledge of the modified photon to locate the target. Using a phase conjugate receiver, entangled signal-idler pairs are jointly detected. The corresponding receiver operating characteristic (ROC) curve tells us how well the system is expected to perform. These findings represent our recommended approach for a microwave quantum radar for long-range target detection in terms of maximum dynamic bandwidth and ROC candidate.

Alessandro Laneve, *Sapienza University of Rome (Italy)*

Experimental strategies for the identification of high-dimensional single photon states produced by quantum dots

Abstract:
The ability to correctly identify quantum states is crucial in many quantum information and communication tasks. Therefore, finding new and more efficient strategies for discriminating quantum states as well as their experimental implementation is an important step in the quest for developing more powerful quantum technology. Photonics represent the most suitable platform for the realization of such protocols; in particular, strategies relying on single photons are endowed with intrinsic security features for application to the quantum communication framework. We present the experimental realization of a time-multiplexing strategy allowing the discrimination of eight quantum states featuring the minimum achievable error probability, by means of a procedure that may be straightforwardly scaled up to supplemental degrees of freedom. The quantum states are written in the four-dimensional Hilbert space represented jointly by light polarization and photons wavelength. Our experiment relies on a bulk optics state receiver of our design and single photons generated by a nearly deterministic solid-state source, characterized by some unique features enabling the protocol. In addition to its direct results, our work delivers further implications: we provide a novel approach to high-dimensional quantum encoding and decoding, harnessing photon energy and detection time; we are able to realize such strategy by means of a simple and scalable setup, consisting of linear optics and two photodetectors only, and we further demonstrate the fruitful employment of Quantum Dot light for quantum information tasks thanks to its distinctive and favorable features.

Ewelina Lange, *Adam Mickiewicz University (Poland)*

Breaking the equivalence between Hamiltonian and Liouvillian exceptional points by thermal photons

Abstract:
Exception points (EPs) are degeneracies of non-Hermitian Hamiltonians that are receiving a lot of attention due to the numerous novel phenomena occurring in their vicinity. Less than four years ago, Minganti et al. [1] pointed out that EPs derived from non-Hermitian Hamiltonians (HEPs) do not take into account quantum jumps, which are present in all fully quantum systems. Therefore, they proposed to derive EPs from the Liouville operator (LEPs), which contains a complete quantum description of an open system. In general, LEPs are different from HEPs in the sense that the position of both in the parameter space is different. However, theoretical studies conducted so far have shown that in some systems LEP can be equivalent to HEP, i.e., that the position of both in the parameter space is the same. The knowledge of the exact position

of EP is important to the phenomena occurring in their vicinity. For example, it is important for the improvement of unconventional photon blockade [2]. Therefore, the introduction of the idea of LEP by Minganti et al. [1] by has triggered impressive research interest in investigating LEPs and comparing them to HEPs.

Here, we study a quantum system consisting of two laser-driven dissipative coupled optical cavities [3,4]. The non-Hermitian Hamiltonian describing this system is not PT-symmetric, because it does not include an incoherent gain term. Nevertheless, we find the position of the HEP by revealing the hidden PT-symmetry via damping frame (DF). We show that in the optical regime LEP is equivalent to HEP, but in the microwave regime this equivalence depends on thermal photons present in the environment. Therefore, we report the phenomenon of breaking the equivalence between LEP and HEP by a non-zero number of thermal photons [3].

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https://doi.org/10.1038/s41598-020-76787-8

Calamanciuc Madalin-Mihai, *University of Bucharest*, Bucharest*, (Romania)*

Gaussian Quantum Entanglement in Curved Spacetime

Abstract:
The effect of Hawking radiation on the quantum entanglement for two mode Gaussian states in the background of a Schwarzschild black hole is investigated. We show that for a squeezed thermal state of a two-mode bosonic system the Hawking radiation reduces and even can destroy the entanglement between the mode observed by an inertial observer Alice and the mode of an accelerated observer Bob who hovers outside the event horizon of the black hole, while it increases and even can generate quantum entanglement between Bob and an imaginary observer anti-Bob inside the event horizon. It is shown that in both these scenarios the competition between the contrary influences produced by the Hawking temperature, squeezing parameter and frequency of the field, may facilitate the preservation of the quantum entanglement.

Koushik Mandal, *IIT Madras (India)*
A complete study of entanglement dynamics of Intensity dependent double Jaynes-Cummings model

Abstract:
The entanglement dynamics between atom-atom, atom-field and field-field systems have been studied for the double Jaynes-Cummings model (DJCM) and the intensity-dependent double Jaynes-Cummings model (IDDJCM). The Jaynes-Cummings is an atom-photon model where the atom interacts with a photon (radiation). In our study for the radiation field, we consider the following states viz, coherent state, squeezed states and binomial states. For the atomic state, we consider a two-level system which is Werner type state. As a measure of entanglement, we use Wootter's concurrence to find the atom-atom entanglement. For the atom-field entanglement and the field-field entanglement, we study the negativity. The reason being that concurrence can be computed only for 2 X 2 systems, whereas negativity can be computed for any system. The dynamics of entanglement for the different fields have been compared with each other in DJCM and IDDJCM models.
The effects of spin-spin interaction between the atoms and the effects of detuning on entanglement are also studied. Through a proper choice of these parameters, we can remove the entanglement sudden deaths (ESD) from the dynamics. The effects of Kerr-nonlinearity on the entanglement dynamics have also been investigated.

Aldo Martinez-Becerril, *University of Ottawa (Canada)*
Reconfigurable unitary transformations of optical beam arrays

Abstract:
Spatial transformations of light are ubiquitous in optics, with examples ranging from simple imaging with a lens to quantum and classical information processing in waveguide meshes. Multi-plane light converter (MPLC) systems have emerged as a platform that promises completely general spatial transformations, i.e., a universal unitary. However until now, MPLC systems have demonstrated transformations that are far from general, e.g., converting from a Gaussian to Laguerre-Gauss mode. Here, we demonstrate the promise of the MLPC, the ability to impose an arbitrary unitary transformation that can be reconfigured dynamically. Specifically, we consider transformations on superpositions of parallel free-space beams arranged in an array, which is a common information encoding in photonics. We test the full gamut of unitary transformations for a two-beam array and make a map of their fidelity. We obtain an average transformation fidelity of 0.85 ± 0.03. This high fidelity suggests MPLCs are a useful tool implementing the unitary transformations that comprise quantum and classical information processing.

István Márton*, Institute for Nuclear Research,* (Atomki) *(Hungary)*
Certification of quantumness in the prepare-and-measure scenario

Abstract:
Quantum phenomena enables strong correlations between the outcomes of spatially separated measurements performed by independent observers. These correlations enable us to distinguish the classical and quantum origins of the experiments. Paradigmatic examples are Bell nonlocality and Einstein-Podolsky-Rosen (EPR) steering. Recently, a similar distinction between classical and quantum features was found in a setup closely related to quantum communication tasks, the so-called prepare-and-measure (PM) scenario [1]. This scenario can be viewed as a communication game between two parties, Alice (the sender) and Bob (the receiver), where the dimension of the classical (versus quantum) system communicated from Alice to Bob is bounded from above.
We have tested the quantumness of two-dimensional systems in the PM scenario, with n preparations and m

binary-outcome measurement settings, where n and m fall well into the range of 70. In the one-qubit PM scenario, a two-level system is transmitted from the sender to the receiver. In this setup, a real n × m matrix M defines the coefficients of a linear witness. We denote by L2(M) the exact value of the one-bit bound associated with matrix M. We found efficient numerical algorithm, namely the see-saw type algorithm for computing L2(M). If this bound is exceeded, we can detect both the quantumness of the prepared qubits and the quantumness (i.e. incompatibility) of the measurements.
We introduced a new constant KD which is related to the finite detection efficiency threshold of Bob's measurements. As an application of the above algorithm we established the lower bound 1.5682 le KD [2].

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Gianlorenzo Massaro, *Istituto Nazionale di Fisica Nucleare - Sezione di Bari (Italy)*
3D correlation imaging at 10 fps

Abstract:
Correlation plenoptic imaging (CPI) is a technique capable of reconstructing a three-dimensional scene by measuring correlations between light intensity fluctuations on two camera sensors. The correlation function measured in CPI contains light-field information, namely, combined knowledge of the intensity distribution of light in the scene and its propagation direction. The correlation-based approach yields two main advantages over conventional light-field imaging architectures, which accesses the light field by including an array of lenslets in the optical device. In fact, whereas the best optical resolution achievable is drastically reduced by the lenslets, CPI is capable of Rayleigh-limited resolution in one, or even two, axial planes of the scene. Moreover, even outside of the planes at best resolution, CPI offers a remarkable resolution advantage.
On the downside, potential real-life applications of high-resolution quantum 3D imaging have been so far limited by the need to collect a large number of statistical realization of the light source, in order to evaluate the correlation function with sufficient signal-to-noise ratio. This issue can be addressed both via hardware, by developing extremely fast high-resolution detectors for speeding-up the frame collection process, and also by optimizing the data analysis protocols, so as to maximize the amount of information extracted by each frame and reduce their required number.
By using a 512x256 array of single-photon avalanche diodes (SPAD), capable of acquiring about 100 kframes per second, we have shown that CPI can acquire up to 10 volumetric images per second, an unprecedented speed for a correlation-based imaging technique. Such performance has been obtained by exploiting correlations from a pseudo-thermal source at the single photon level, as enabled by the SPAD array.
From a data analysis perspective, we have been working on approaches based on deep-learning and compressive sensing, which have proven capable of reconstructing images with high signal-to-noise ratio, needing only a fraction of the frames typically needed by simple statistical averaging for reaching the same image quality.

Themistoklis Mavrogordatos, *ICFO -- The Institute of Photonic Sciences (Spain)*

Conditional separation of timescales in the strong-coupling limit of qed: a contextual unraveling of multi-photon resonances

Abstract:
In the open driven Jaynes-Cummings (JC) model, multi-photon resonances occur as a result of the ``quantum jumpiness" in matter [1], for a scattering process fundamentally affected by the inputs and outputs -- information is read off two channels linked to a system comprising a two-level atom strongly coupled to a resonant coherently driven cavity mode. The special role of quantum fluctuations in this model is captured by the breakdown of photon blockade by means of a dissipative quantum phase transition [2, 3]. To resolve the associated strong-coupling ``thermodynamic" limit [4], we focus on the buildup and collapse of phase-space multimodality for weak driving, where a perturbative treatment is possible. Correlation functions of the forwards and side-scattered photons provide an alternative perspective, uncovering conditional and contextual dynamics that are shaped by features unique to the ladder of dressed JC eigenstates [4]. Finally, we show that the response of this exemplary quantum nonlinear cavity QED source is appropriate for revisiting wave/particle duality through conditional balanced homodyne detection [1, 5].

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Tatiana Mihaescu, *Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (Romania)*

Steering witnesses for unknown Gaussian quantum states

Abstract:
We define and fully characterize the witnesses based on second moments detecting steering in Gaussian states by means of Gaussian measurements. All such tests, which arise from linear combination of variances or second moments of canonical operators, are easily implemented in experiments. We propose also a set of linear constraints fully characterizing steering witnesses when the steered party has one bosonic mode, while in the general case the constraints restrict the set of tests detecting steering. Given an unknown quantum state we implement a semidefinite program providing the appropriate steering test with respect to the number of random measurements performed. Thus, it is a ”repeat-until-success” method allowing for steering detection with less measurements than in full tomography. We study the efficiency of steering detection for two-mode squeezed vacuum states, for two-mode general unknown states, and for three-mode continuous variable GHZ states. In addition, we discuss the robustness of this method to statistical errors.

Sidali Mohammdi, *University of Abderahmene Mira Bejaia (Algeria)*

Optimal estimation of a weak coupling parameter in quantum systems: a comparative analysis

Abstract:
This poster presentation focuses on the estimation of an unknown coupling parameter λ in quantum systems governed by a weakly perturbed Hamiltonian $H = H0 + \lambda H1$. exploiting the principles of quantum estimation theory, we investigate the optimal conditions required for accurate estimation and assess the achievable precision limit. Our study considers two scenarios: the first scenario involves measurements limited to the ground state of the system, while the second scenario incorporates an initial state preparation followed by measurements after free evolution.
We demonstrate that the ultimate precision limit, known as the Cramer-Rao limit, for one-parameter estimation can be attained. Moreover, we identify the specific conditions necessary to achieve this limit in both scenarios. Through a comparative analysis, we explore the most informative approach in terms of initial state preparation, optimal measurement strategy, and the optimal timing for measurements.

By investigating the estimation of the coupling parameter λ, this study contributes to the advancement of quantum systems' characterization and paves the way for improved understanding and control of quantum phenomena.

Jürgen Mony, *CNR-INO (Italy)*

Frequency tuning of molecular emitters by the combination of optical bursts and electric field

Abstract:
The local control of charge transport and of electric fields around quantum emitters in the solid state is a fascinating field of research with a clear impact on quantum technologies. Indeed, single molecules in appropriate host matrices are an example of extraordinary well-behaved single photon sources, whose control and scalability are crucial tasks. In particular, centrosymmetric dibenzoterrylene (DBT) molecules in anthracene are known to respond only at the second order to an applied electric field, exhibiting a quadratic Stark coefficient at cryogenic temperatures. This is traditionally observed by applying a voltage difference to electrodes on both sides of the molecule and correspondingly detecting a parabolic shift of the molecule main optical transition (ZPL). Here, we investigate how our control over the local environment can be further extended by coupling it with the more recently observed optical induced shift of the ZPL. In particular we show that the origin of the parabola associated to the quadratic Stark effect can be shifted by a combination of a focused laser beam and an applied electric field. The optical burst of the focused laser beam leads to a photoionization cascade, in which the created charge carriers counterbalance the applied electric field. The shift of the parabola can be controlled by the strength of the applied electric field. By only using the optical burst without any applied electric field the shift can be reversed and the parabola goes to its initial position. This process can be used to tune the molecular transition in a range of several GHz. Therefore, the process of the optical burst in combination with an applied electrical field is a powerful tool to tune the transition frequencies of organic molecules at cryogenic temperatures.

Darren Moore, *Palacky University (Czech Republic)*
Nonlinear squeezing thresholds in quantum and classical mechanics

Abstract:
The motion of a linear mechanical system, characterised by its mass and an up-to-quadratic potential, possesses a limited capacity to reduce noise in nonlinear combinations of the canonical variables. This limitation induces thresholds for noise reduction in nonlinear variables beyond which linear mechanical oscillators cannot pass. For quantum mechanics, this limitation can be leveraged into a threshold for quantum non-Gaussianity based on the observation of nonlinear squeezing. If a state is observed with statistics below the threshold then it cannot be represented by any mixture of Gaussian states. Furthermore, such thresholds may be extended to enclose greater classes of states beyond the convex closure of the Gaussian states by incorporating higher-than-quadratic nonlinearities. At the same time, a classical a particle in a noisy, damped, up-to-quadratic potential cannot achieve arbitrarily low nonlinear squeezing. We derive thresholds, with temperature bounded from below, so that if sufficient nonlinear squeezing is observed such models of linear motion can be rejected and the motion is conclusively nonlinear. These thresholds are constructed out of accessible statistical quantities, relying only on position and momentum measurements, and can be surpassed with state-of-the-art nanomechanical systems implementing cubic or quartic (Duffing) nonlinearities. By approaching these witnesses of nonlinearity from both the classical and quantum sides, we highlight the possibility to shed light on transition between quantum and classical behaviour.

Daniele Morrone, *Università degli studi di Milano (Italy)*
Daemonic ergotropy in continuously-monitored open quantum batteries

Abstract:
The amount of work that can be extracted from a quantum system can be increased by exploiting the information obtained from a measurement performed on a correlated ancillary system. The concept of daemonic ergotropy has been introduced to properly describe and quantify this work extraction enhancement in the quantum regime. We explore the application of this idea in the context of continuously-monitored open quantum systems, where information is gained by measuring the environment interacting with the energy-storing quantum device. We show that the corresponding daemonic ergotropy takes values between the ergotropy and the energy of the corresponding unconditional state. The upper bound is achieved by assuming an initial pure state and a perfectly efficient projective measurement on the environment, independently of the kind of measurement performed. On the other hand, if the measurement is inefficient or the initial state is mixed, the daemonic ergotropy is generally dependent on the measurement strategy. This scenario is investigated via a paradigmatic example of an open quantum battery: a two-level atom driven by a classical field and whose spontaneously emitted photons are continuously monitored via either homodyne, heterodyne, or photo-detection.

Michele Nicola Notarnicola, *Università degli studi di Milano (Italy)*
Optimizing state-discrimination receivers for continuous-variable quantum key distribution over a wiretap channel

Abstract:
We address a continuous-variable quantum key distribution (CV-QKD) protocol employing quaternary phase-shift-keying (QPSK) of coherent states and a non-Gaussian measurement inspired by quantum receivers minimizing the error probability in a quantum-state-discrimination scenario. We assume a pure-loss quantum wiretap channel, in which a possible eavesdropper is limited to collect the sole channel losses and we design an optimized receiver maximizing the key generation rate (KGR), namely the key-rate optimized receiver (KOR), comparing its performance with respect to the pretty good measurement (PGM) and the heterodyne-based protocol. We show that the KOR increases the KGR for metropolitan-network distances. Finally, we also investigate the implementations of feasible schemes, such as the displacement feed- forward receiver, obtaining an increase in the KGR in particular regimes.

Koryun Oganesyan*, Institute of Experimental Physics SAS (Slovakia)*
Polarimetric local diagnostics of plasma by stimulated nonlinear resonance rotation of probe signal

Abstract:
The polarization plane stimulated rotation angle of probe signal in the intense laser field in plasma is calculated. The estimates of the residual gas local density in a cesium plasma based on the effects of Faraday, Cotton-Mouton and stimulated rotation of probe signal in the intense laser field have been found. A brief theory of resonant change in the plane of polarization of a probe signal under the action of an intense pulse is presented. It is shown, that the rotation in the medium has a complex structure.

Adrian Ortega*, Wigner Research Centre for Physics (Hungary)*
Benchmarking quantum computers using quantum state matching of qubits

Abstract:
We present our advances on the implementation of a measurement-induced nonlinear protocol for quantum state matching using some commercially available quantum computers. Using this implementation, we present a benchmark that detects quantitatively the device specific errors. In contrast to current benchmarks trends, our circuit is a non-random deep circuit. Among the devices analyzed, we discuss briefly which are more promising.

Nishant Kumar Pathak*, Indian Institute of Technology Delhi (India)*
265 km fiber quantum key distribution using differential phase shift protocol at 2.5 ghz clock

Abstract:
Differential Phase Shift QKD (DPS-QKD), known for its simplicity and high key rate for fiber quantum communication [1], is also resistant to attacks, including those based on photon-number-splitting (PNS) and coherent attacks. Phase encoding makes it less susceptible to noise and other types of interference, making it a perfect fit for QKD through fiber channels. DPS-QKD can secure network communication, such as in the case of secure routing and authentication in the Internet of Things (IoT) and other communication networks

[2]. DPS- QKD has been used to implement various cryptographic protocols, such as quantum digital signatures [3] and quantum secret sharing [4].
The reported experiments implementing the DPS protocol are limited in the secure key rate, channel loss, or communication length. The work in [5] is limited in secure key rate to only 99.2 bps for 205 km, [6] operates at only 1 GHz with a communication distance of only 105 km. The experiment reported by Diamanti et al. in [7] running at 1 GHz was limited to 100km with only a 166 bps key rate. Also, previously best performance with standard telecom fiber, reported in [5], has QBER and communication length limited to 3.45% for 52.9 dB loss, respectively.
In this experiment a CW laser centered at a wavelength of ITU channel 22 was first modulated into a 2.5 GHz pulse train by an intensity modulator (IM). The IM was driven by a Field programmable gate array (FPGA). A phase modulator (PM) was used to encode the pulses with random bit sequences with a phase of either 0 or pi. The encoded pulse train is then attenuated to the required mean photon number. At Bob's end, the sequential pulses were interfered using a 1-bit delay. The two outputs of the MZI are then connected with Super-conducting Single Photon Detectors (SNSPDs) and the time stamps of clicks were analyzed. We achieved a secure key rate of more than 150 bits/s for a channel length of 265 km. This is the first secure key distribution using DPS QKD at 2.5 GHz.
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Soumyabrata Paul, *Indian Institute of Technology Madras (India)*

Identification of links between entropic uncertainty relations and quantum entanglement through optical tomograms

Abstract:
The entropic uncertainty relations (EUR) have been quantified and extensively investigated in the literature in various contexts, including their links with entanglement, as they subsume the familiar Heisenberg uncertainty principle. They find several applications in quantum information and metrology. They have been examined in spin systems, and also with polarization states of light, both for entangled pure and mixed Bell-like states. However, examining EURs and their links with entanglement is challenging wherever state reconstruction is a formidable task, as with continuous variable (CV) systems and hybrid quantum (HQ) where the Hilbert space is large. An alternative approach is to extract as much information as possible in this context directly from optical tomograms (which are histograms readily available from experiments). The detailed procedure to extract different tomographic entanglement indicators (TEIs) directly from tomograms, avoiding state reconstruction, has been reported in earlier literature. Here, we illustrate how both EURs, and the manner in which they change during the dynamics of CV systems, can be easily extracted solely from appropriate slices of these tomograms. Further, as every tomogram is a set of probability distributions assembled together in a pattern, changes in these patterns with dynamics can be assessed through the Wasserstein distance (WD), the Kullback-Leibler (KL) divergence etc., which compare the similarity between patterns. The WDs and KL divergence are ideally suited for machine learning algorithms, for tomography.

We examine the efficacy of different bipartite TEIs, WDs computed from tomographic slices (p-slice Wasserstein distance), and the KL divergence, in mimicking the dynamics of the EURs in canonically conjugate slices, in two generic CV and HQ systems. These are (a) a multilevel atom modelled as a

nonlinear oscillator interacting with the quantized radiation field, and (b) a $Lambda$-atom interacting with two radiation fields with Kerr nonlinearity. The former allows us to probe the role played in this exercise, by the initial state of light and the ratio of the strengths of interaction and nonlinearity, while the latter examines the effect of mixed state entanglement between the two fields. This effort also helps in identifying the subset of TEIs, which capture the dynamics of EURs. Further, the performance of WDs and KL divergence in this investigation facilitates assessment of their possible usefulness in generative adversarial networks in learning protocols pertaining to CV tomograms, with special reference to optics.

Matteo Piccolini, *Università degli Studi di Palermo (Italy)*

Asymptotically-deterministic robust preparation of maximally entangled bosonic states

Abstract:
We introduce a theoretical scheme to prepare a pure Bell singlet state of two bosonic qubits, in a way that is robust under the action of arbitrary local noise. Focusing on a photonic platform, the proposed procedure employs passive optical devices and a polarization-insensitive, non-absorbing, parity check detector in an iterative process which achieves determinism asymptotically with the number of repetitions. Distributing the photons over two distinct spatial modes, we further show that the elements of the related basis composed of maximally entangled states can be divided in two groups according to an equivalence based on passive optical transformations. We demonstrate that the parity check detector can be used to connect the two sets of states. We thus conclude that the proposed protocol can be employed to prepare any pure state of two bosons which are
maximally entangled in either the internal degree of freedom (Bell states) or the spatial mode (NOON states).

Eloy Piñol Jimenez, *ICFO - The Institute of Photonic Sciences (Spain)*

Experimentally accessible quantum-trajectory predictions to distinguish different unravelings via nonlinear averages

Abstract:
We discuss a way to experimentally distinguish between different unravelings of the GKSL master equation (ME) [see Dalibard et al., Phys. Rev. Lett. 68 (5), 580 (1992); D. Keys and J. Wehr, J. Math. Phys. 61, 032101 (2020)], appealing to stochastic conditional dynamics via quantum trajectories (QT). Our proposal is based on performing a nonlinear operation on single-trajectory quantum mechanical averages (STQMA) – in principle accessible to the experimenter – and subsequently averaging over all different realizations comprising the ensemble. In the spirit of complementarity, there are different environments that might be encountered by the scattered field, all consistent with the validity of the ME. In order to tell them apart, we have focused on the paradigmatic quantum nonlinear system of resonance fluorescence for the two most popular unravelings: the Poisson-type – corresponding to direct detection of the photons scattered from the two-level emitter – and the Wiener-type, revealing other attributes of the scattered field in addition to particle number, such as the wave amplitude and the spectrum. For the Poisson-type unraveling we rely on the Dyson expansion of the density operator, extended to account for the squaring of the STQMA onto the two-level system observables. We calculate two variances commonly met when treating the state vector as a random variable in Hilbert space, whose sum gives the ordinary quantum variance [H.-P. Breuer and F. Petruccione, The Theory of Open Quantum Systems, Sec. 5.1, OUP (2007)]. The asymptotic results extracted for weak and strong coherent driving of the atom are in very good agreement with the Monte-Carlo simulations yielding the variances in question. In support of the obtained analytical and numerical variance evolutions, for both types of unraveling, an alternative asymptotic method is developed based on the expansion of the moments whose behaviour is governed by the adjoint Lindbladian of resonance fluorescence. While a comparison with the fluorescent signal emitted from a single trapped Rb atom [L. Bianchet, N. Alves, L. Zarraoa et al., Manipulating and measuring single atoms in the Maltese cross

geometry, Ver. 2, Open Res. Eur. 1 (2021); N. Bruno, L. C. Bianchet, V. Prakash, et al., Maltese cross coupling to individual cold atoms in free space, Opt. Express 27, 31042 (2019)] is underway, our proposal can be readily extended to account for open quantum systems with more degrees of freedom.

Domenico Pomarico, *University of Bari & INFN Bari (Italy)*

Dynamical quantum phase transitions of the Schwinger model: real-time dynamics on IBM quantum

Abstract:
Simulating the real-time dynamics of gauge theories represents a paradigmatic use case to test the hardware capabilities of a quantum computer, since it can involve non-trivial input states' preparation, discretized time evolution, long-distance entanglement, and measurement in a noisy environment. We implemented an algorithm to simulate the real-time dynamics of a few-qubit system that approximates the Schwinger model in the framework of lattice gauge theories, with specific attention to the occurrence of a dynamical quantum phase transition. Limitations in the simulation capabilities on IBM Quantum were imposed by noise affecting the application of single-qubit and two-qubit gates, which combine in the decomposition of Trotter evolution. The experimental results collected in quantum algorithm runs on IBM Quantum were compared with noise models to characterize the performance in the absence of error mitigation.

Attila Portik, *Wigner Research Centre for Physics (Hungary)*

Effect of coherent errors on iterated nonlinear quantum protocols

Abstract:
We study the effect of coherent quantum logic gate errors on a specific iterated quadratic nonlinear quantum protocol. We assume a scenario, where the coherent error affects the Hadamard gate that is applied in every step of the protocol. We determine the relations describing the evolution of an arbitrary (pure or mixed) qubit state and examine the effects of the occurring coherent gate errors. We show that for small coherent errors, the characteristic properties of the protocol are slightly distorted: in the preparation-noise-free case the attractive pure states are displaced, and the border of their convergence regions are deformed, but the fractal nature of this border remains, and even its fractal dimension is not significantly changed. In the case when preparation noise is also present, we show that all relevant features of the coherent-error-free case survive, namely, the invariant plane still exists and contains the relevant fixed points and cycles of the dynamics, which are slightly shifted, and the border of the convergence regions continues to be a fractal, though, similarly to the pure case, somewhat deformed. We also investigate the most notable characteristic of the original protocol, namely, the preparation noise tolerance property, manifested as a first-order phase transition of the fractal dimension of the border of convergence regions as a function of the initial purity. We show that the presence of small coherent errors does not destroy this property, although the critical purity of the phase transition shifts from its original value. Remarkably, we find that as a result of the distortion of the convergence regions on the invariant plane of the dynamics, the critical purity cannot always be identified with the same type of repelling point as in the coherent-error-free case, but rather with its lowest purity preimage on the invariant plane.

Kacper Prech, *University of Basel (Switzerland)*

Quantum fluctuation theorem for arbitrary measurement and feedback schemes

Abstract:
Fluctuation theorems and the second law of thermodynamics are powerful relations constraining the behavior of out-of-equilibrium systems. While there exist generalisations of these relations to feedback controlled open quantum systems, their applicability is limited, in particular when considering strong and continuous measurements. In this letter, we overcome this problem by deriving a novel fluctuation theorem, and the associated second law, which remain applicable in arbitrary feedback control scenarios. A crucial ingredient in our fluctuation theorem is provided by the entropy production which is inferrable from the measurement outcomes, an experimentally accessible quantity
that does not diverge even under strong continuous measurements. Our results are derived using two frameworks: a quantum jump unravelling of the master equation and a unitary evolution of the joint quantum state of the system and the envoronment. We illustrate our results by a qubit undergoing a continuous measurement, where our approach provides a useful bound on the entropy production for all measurement strengths.

Andrei Rasputnyi, *Max Planck Insitute for the Science of Light (Germany)*

Enhancement of two-photon processes driven by highly multimode squeezed vacuum

Abstract:
Nonlinear spectroscopy and microscopy have become indispensable tools in solid-state physics and biomedical research. These techniques are based on multi-photon processes, typically requiring high light flux, which can be a problem for samples with a low optical damage threshold. The use of nonclassical states of light can improve the efficiency of multi-photon processes while remaining in the low-flux regime. In particular, squeezed vacuum state generated via parametric down-conversion (PDC) is found to be advantageous for exciting two-photon absorption (TPA) and sum frequency generation (SFG). When a squeezed vacuum has much less than one photon per mode, which happens under low-gain regime of PDC, the rate of any two-photon process scales linearly with excitation photon flux whereas the scaling is quadratic for coherent light. The rate of two-photon processes remains low due to the low overall efficiency. This issue can be solved by increasing the number of frequency and angular modes of squeezed vacuum involved in the two-photon process. It is shown theoretically for TPA [M. Raymer and T. Landes. Phys. Rev. A 106, 013717 (2022)] that there is no advantage of making the frequency bandwidth of squeezed vacuum larger than two-photon resonance linewidth. However, there are no restrictions for the angular bandwidth of squeezed vacuum in the case of TPA, which allows the use of a large number of angular modes making two-photon process signal more accessible.

In this work, we study both experimentally and theoretically the effect of the number of spatial modes of squeezed vacuum on the rate of SFG. Using 0.5 mm thick PPLN crystal and 800 nm picosecond pump, we generate broadband PDC radiation with an 800 nm bandwidth around 1600 nm. According to the theoretical estimations, a squeezed vacuum has approximately 100 frequency and 100 angular modes. The second PPLN crystal, identical to the first one, is used for SFG. We observe the change of SFG scaling from linear to quadratic one when the mean number of PDC photons per mode becomes larger than one. For the first time, we show experimentally and theoretically that the rate of SFG increases with the increase of the number of angular modes in the low-gain regime. The developed approach of angular modes of squeezed vacuum broadens the scope of applications of TPA microscopy.

Sholeh Razavian, *LMU Munich/ MPQ (Germany)*
Multi-photon coherence and interference

Abstract:
we are considering multi-photon interference including decoherence effects. The polarized photons propagate in integrated waveguide arrays with polarization-dependent coupling.
We analyze multiphoton coincidence measurements and sample from the probability distribution in order to investigate polarization-dependent decoherence of the total quantum state.

Enrico Rebufello, *INRIM (Italy)*
Robust weak measurement: extracting anomalous weak values from a single photon

Abstract:
Weak values (WVs) are one of the most interesting and intriguing quantum measurement paradigms. Their exotic traits, such as the possibilities of yielding anomalous values (i.e., values not bounded by the observable eigenvalue spectrum, and even imaginary ones), have been demonstrated and exploited in many quantum metrology and quantum information applications. Nevertheless, WVs still remain a controversial topic: one of the main objections against them, e.g., comes from the fact that they require a weak coupling followed by a post-selection. Due to weak coupling, the WV can only be extracted by averaging over a very large number of readings. While averaging is a standard practice, its combination with post-selection is not, hence the legitimacy of the WV statistical estimation has been questioned.

To reach a conclusive point in this debate, we devised and experimentally demonstrated the so-called Robust Weak Measurement (RWM) [1], a novel weak-interaction-based measurement protocol in which, instead of averaging over multiple acquisitions, even a single reading of the measuring device provides a reliable estimate of a (anomalous) WV.

In our proof-of-principle experimental implementation of the RWM, we decided to extract the WV of the polarization of a single photon, sent through a series of N=7 identical preparation + weak coupling + post-selection stages, attuned to detect an arbitrary (anomalous) WV. Our results highlight the RWM unprecedented capability of extracting a (anomalous) WV even from a single detection event, stressing the non-statistical, single-particle nature of WVs. Furthermore, the experiment suggested a viable possibility for iterative amplification methods, paving the way for future practical applications in quantum metrology and other quantum-technology-related fields.

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Klaus Renziehausen, *Friedrich Schiller University Jena (Germany)*
How to control the population of electronic dark states in aggregates via spatial phase shifts in the near-field of plasmonic nanoparticles

Abstract:
We demonstrate a new ansatz how to use nanoplasmonics for the control of the population of states in an aggregate. From the excitonic excited states of this aggregate, some states are optically accessible, while others are optically dark – and our goal is to find a way to populate and control the population of these dark states to store and release energy on demand.

In our model, we place this aggregate near a nanoparticle and an incident laserpulse is interacting with this system thus creating a strong exponentially localized near-field.

As a consequence, the aggregate is interacting with the superposition of the incident field and the near-field of the nanoparticle. Both amplitude and phase of this superposition field depend then on the distance to the nanoparticle – therefore the field strength at the positions of different monomers of the aggregate varies. This spatial variation breaks the symmetry and enables an excitation of states, which were without this symmerty breaking optically dark.

Intuitively, one might think that the spatial decay of the amplitude is the most important parameter to control the population of the formerly dark states and the spatial dependency of the phase of the superposition field is less important. However, our analysis shows that this phase plays a key role to control the population of these states.

We present both an analytical framework and the results of quantum dynamical simulations to demonstrate this key role of the phase. In particular, our numerical results demonstrate that the phase can be used to control which of the monomers of a dimer or a quadrumer are preferentially excited by the superposed field.

Atirach Ritboon, *Thammasat University (Thailand)*
Nonlinear bosonic Maxwell's demon

Abstract:
Maxwell's demon principle of extracting valuable resources through measuring fluctuations in the system already stimulated modern quantum physics. In contrast to classical physics, a free coupling to a probe and its free measurement fundamentally shape the system state. This becomes a new dimension of the Maxwell demon effect, as in addition to the gained information, the back action on the system can be exploited and essential for further applications. We investigate quantum bosonic Maxwell's demon coupled to a two-level system to address this issue straightforwardly. The deterministic multiple subtractions of energy quanta by an energetically conservative Jaynes-Cummings interaction leads to an out-of-equilibrium state. Although still super-Poissonian, it can resonantly excite another two-level system better than any thermal state. To further reduce the super-Poissonian statistics close to a Poissonian by a Maxwell's demon operation and increase the excitation rate, we suggest subsequent use of still energetically conservative multiphonon subtractions performed by an available nonlinear Jaynes-Cummings interaction. The optimal combination of both deterministic subtractions leads to statistics that approaches a Poissonian distribution otherwise produced by shot-noise-limited sources as an ideal laser requiring extreme bosonic nonlinear saturations.

Áron Rozgonyi, *Wigner Research Centre for Physics (Hungary)*
Break-even point of the quantum repetition code

Abstract:
Enhancing the lifetime of qubits with quantum code-based memories on different quantum hardware is a significant step towards fault-tolerant quantum computing. We theoretically show that the break-even point, i.e., preserving arbitrary quantum information longer than the lifetime of a single idle qubit, can be beaten even with the quantum phase-flip repetition code in a dephasing-time-limited system. Applying circuit-based analytical calculation, we determine the efficiency of the phase-flip code as a quantum memory in the presence of relaxation, dephasing, and faulty quantum gates. Considering current platforms for quantum computing, we identify the gate error probabilities and optimal repetition number of quantum error correction cycles to reach the break-even point.

Madhavakkannan Saravanan, *University of Basel (Switzerland)*
Storing single photons in a ground state rb vapour-cell memory.

Abstract:
Quantum memories are a key ingredient for the realization of quantum networks [1]. Furthermore, they allow the synchronization of probabilistic single photon sources significantly enhancing the generation rates of multiphoton states [2]. We implemented a broadband, optical quantum memory in hot Rb vapor with on-demand storage and retrieval [3]. With a bandwidth matched spontaneous parametric downconversion (SPDC) source, we can generate heralded single photons suited for storage with a heralding efficiency ≈ 40% [4]. We report on our recent achievements in storing SPDC single photons with a linewidth of 370MHz with an end-to-end efficiency ηe2e ~1% for a storage time of T = 160ns. A signal to noise ratio of ~10 and a memory lifetime τ = 380ns are achieved. The measurement of the second order autocorrelation of retrieved single photons results in g(2) ~ 0.2, showing that the non-classical properties of the stored light are maintained.

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Gniewomir Sarbicki, *Nicolaus Copernicus University (Poland)*
Detecting non-locality between modes of light using Mach-Zender interferometers

Abstract:
We discuss the detection of non-locality in a two-mode state of light by violating Bell inequalities: CHSH and its generalisations. We assume that each party uses a photodetector proceeded by a Mach-Zender interferometer fed with a strong coherent state on the second input, thus realising a displacement operator. We compare the violation achievable restricting to such observables with the quantum bound. Finally, we discuss the maximal possible violation when restricting to families of experimentally achievable states.

Dennis Scharwald, *Paderborn University (Germany)*

Multimode su(1,1) interferometers at high gain

Abstract:
In classical interferometers, the phase sensitivity for measuring the interferometric phase is bounded by the shot noise limit (SNL). Nonlinear SU(1,1) interferometers provide a convenient way for surpassing the SNL and constitute an important tool for quantum metrology [M. V. Chekhova and Z. Y. Ou, Adv. Opt. Photon. 8, 104 (2016)]. Such interferometers are based on nonlinear processes such as parametric down-conversion (PDC), where the pump photon is split into one signal and one idler photon. After acquiring some relative phase shift, the PDC radiation is recombined in another PDC section and amplified or de-amplified, depending on this phase shift. In a single-mode regime, the phase sensitivity of nonlinear interferometers can be improved by increasing the parametric gain [M. Manceau, et al., New J. Phys. 19, 013014 (2017)]. In the multimode scenario, this strategy is not straightforward: To achieve the phase sensitivity below SNL, a proper dispersion or diffraction compensation must be performed. At the same time, the increase in the gain brings the effect of time-ordering into play.

In this work, we present a theoretical approach to the description of multimode nonlinear SU(1,1) interferometers in the high-gain regime. This approach is based on the numerical solution of the set of integro-differential equations for the plane-wave operators [P. R. Sharapova et al., Phys. Rev. Research 2, 013371 (2020)] and allows us to introduce the gain-dependent Schmidt-modes [A. Christ et al., New J. Phys. 15, 053038 (2013)]. We investigate the spatial properties and the phase sensitivity of two types of SU(1,1) interferometers: A regular setup consisting of two consecutive PDC sections and a configuration of two crystals with diffraction compensation. The regular setup has one major disadvantage: the radiation generated in the first crystals has a quadratic phase in the angle of emission, which leads to the fact that different spatial modes are amplified differently. This effectively acts as internal losses that destroy the phase sensitivity at high gain. The quadratic phase can be compensated with the use of a double-pass setup and a spherical mirror which reflects the radiation back to the crystal and compensates for diffraction. Such compensation leads to the simultaneous amplification or de-amplification of all modes, which in turn results in a significant improvement of the phase sensitivity at high parametric gain.

Tom Schmit, *University of Saarland (Germany)*

Quantum theory of self-organization in many–body cavity quantum electrodynamics

Abstract:
Ensembles of atoms strongly coupled with the electric field of an optical cavity offer a formidable laboratory for studying the out-of-equilibrium dynamics of long-range systems in the quantum regime. In this work, we derive by means of the formalism developed in Ref. [1] a quantum master equation describing the dynamics of atoms which interact with a multimode high-finesse cavity. We then analyse the predictions in several relevant limits, namely semi-classical, mean-field, and beyond mean-field. Our theory reproduces the results of the experiment of Ref. [2] and provides a powerful tool for singling out the individual contributions to the onset of metastability in quantum globally-interacting systems.

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Fabrizio Sgobba, *Agenzia Spaziale Italiana (Italy)*
Delayed-choice common-path Hong-Ou-Mandel interference as a tool for entanglement preparation

Abstract:
Hong Ou Mandel (HOM) interference has been first observed more than 30 years ago, pioneering the quantum technology era. Namely, when two completely indistinguishable photons impinge on two ports of a beam splitter (BS), they come out of the same port as a consequence of their bosonic character (effect also referred to as photon bouncing). If an adjustable distinguishability is introduced before one of the input ports, the HOM interference manifest itself as a dip in coincidence events when the maximum degree of indistinguishability is approached. The HOM interference is at the very core of many novel applications for quantum light generation, sensing or testing in the field of fundamental physics, since the measurement of the HOM dip, which depends only on the intrinsic features of the interfering photons, allows to overcome the sensitivity limits imposed by detectors and achieve record-breaking metrological results.
If the two indistinguishable photons impinge on the BS from the same port (in the so-called common-path configuration), the “Welcher-Weg” uncertainty related to the input modes is lost and does not give rise to the interferometric HOM dip unless such uncertainty has been replaced by other degrees of freedom, as for example the polarisation state, time delay or spectral distribution. In this regard, the highly correlated nature of twin photon pairs produced via Type-II parametric down-conversion (PDC) has provided a wealth of interesting new interferometric phenomena. If two photons obtained via PDC and exhibiting orthogonal polarisations impinge on the same port of a beam splitter, the interferometric coincidence pattern could be adjusted by post-selecting the polarisation state right before the detector, obtaining a classical HOM dip or an anti-HOM peak in coincidences (when polarisers on output ports are in diagonal-diagonal or diagonal-antidiagonal configuration respectively), de facto deciding downstream (by polarisation selection) whether the photons on the beam splitter did bouncing or anti-bouncing upstream. Such effect, which appears to violate causality, is usually referred to as “delayed choice”.
In the proposed talk will be presented a comprehensive novel description of delayed-choice common-path HOM interference with PDC-generated photon pairs within the formalism of Quantum Information Theory. The description made it possible to link the coincidence pattern to the density matrix describing the PDC output, allowing the realisation of an entanglement-preparation experimental system capable to tailor a PDC twin photons pair from a totally mixed state to a Bell state, maximising entanglement and violating Bell inequality consistently over time.

Sofia Sgroi, *Queen’s University Belfast (United Kingdom)*
Designing qubit chains for efficient transfer through reinforcement learning

Abstract:
Optimizing excitation and quantum state transfer across complex physical systems is a problem of great importance in a multitude of contexts, in particular in quantum communications [1,2]. Among the various systems, qubit chains are of special interests for quantum communication and quantum computing. These might in particular be useful to connect distinct quantum processors and registers and, for this reasons, various techniques have been developed to realize transport across these structures [3].

Designing optimal couplings among the qubits in such chains would allows us to avoid or minimize the control we have to exert during the system dynamics. While arbitrary couplings engeneering between qubits in a chain can be a difficult task to accomplish for generic physical systems, some platforms where the couplings can be distance-dependent, such as ion traps [4], could allow some degree of control over their design.

Here I show how one could optimize the design of a qubit chain whose interactions are distance dependent (dipole-dipole interactions), considering a one-excitation transfer for simplicity. Dividing the physical space

that separates the input and output qubits in a grid composed of a certain number of sites, I use a bottom up, Reinforcement Learning [5] approach to decide on the number and positions of qubits in such grid. All the qubits interact with each others, rendering the chain equivalent to a fully connected quantum network. The chain can in principle be 1, 2 or 3-dimensional in space. Such approach makes the optimization problem treatable, imposes realistic physical constraints on the choice of the couplings between qubits, is generalizable to other position-based couplings and easily allows for the study of the effects of errors commited in the placement of the qubits, disorder or noise.

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Preeti Sharma, *Indian Institute of Technology Delhi (India)*
Spatial properties of partially coherent down-converted photons

Abstract:
We report the experimental study for spatial properties of partially coherent qubits generated using the spontaneous parametric down-conversion (SPDC) process in a collinear configuration using type-I phase matching in non-linear crystal with a pump beam of a tunable degree of spatial coherence. The spatial profiles of the generated down-converted photons show an asymmetric ring compared to the circular beam expected with a coherent pump, with degradation in the degree of spatial coherence of the pump beam. This implies that the spatial correlations in these photons degrade with the reduction in spatial coherence of the pump. We verified the experimentally observed spatial profiles using theoretical study [1] with the pump as a Gaussian Schell model (GSM) beam. The profiles illustrate the spreading of the SPDC ring in a particular direction when the transverse correlation length of the pump beam decreases. It is observed that a pump beam with a smaller size than the lateral ray displacement destroys the symmetry of the spatial profile due to spatial walk-off. We notice a similar impact as the spatial coherence of the pump beam decreases.
Simulated and experimental profiles demonstrate that the pump walk-off effect increases the value of phase mismatch, leading to an increase in asymmetric broadening in an otherwise symmetric SPDC ring in the opposite direction of the pump's walk-off direction. The effect diminishes when the degree of spatial coherence of the pump is high, implying a large value of correlation length as compared to lateral ray displacement. This study reveals the propagation of optical coherence from the pump to biphotons in the SPDC process [2].
The multimode nature and reduced speckles of partially spatially coherent beams in classical regimes make them an excellent choice for optical communication in free space [3], holography [4], and imaging [5]. A partially spatially coherent pump enables the generated photons to be ideal for ghost imaging and QKD applications involving the transport of quantum information in free space and turbulent media [6,7]. This study concludes that a proper optimization of spatial coherence is required to exploit the maximum benefits of partially coherent qubits with the minimum diffusion of the photons in the transverse plane. This study is thus expected to be helpful in various applications of down-converted photons produced by partially coherent pump fields, such as in free-space quantum communication, quantum key distribution, quantum holography, quantum encryption and quantum imaging.
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Maxim Sirotin, *Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU) (Germany)*

Single-photon generation in a scanning electron microscope with silicon microresonators

Abstract:
Single-photon sources play a crucial role in quantum information technology. Quantum dots and color centers allow the creation of single photons on demand and can be electrically driven [1]. Spontaneous parametric down-conversion and spontaneous four-wave mixing serve as widely tunable sources of heralded single photons and complex quantum states [2]. Controlled emission of single photons from free electrons potentially provides new sources with broad spectrum, high efficiency, and electron-photon entanglement. Free-electron wavefunction pre-shaping enables the construction of photonic cat and Gottesman-Kitaev-Preskill (GKP) states for fault-tolerant quantum computing [3]. Recently, the effect of generating 1550 nm photons from free electrons directly into a silicon nitride ring microresonator in a transmission electron microscope (TEM) at 120 keV has been experimentally shown [4].

We report an approach for generating quantum states of light directly inside integrated silicon-on-insulator (SOI) microcavities based on free electrons propagating close to the microcavity inside a scanning electron microscope (SEM). Our group's recent demonstration of a high-resolution electron spectrometer [5] enables measurement of sub-eV modulations of electron energy and detection of single photon emission events, turning SEMs into tunable single-photon sources with direct relevance to quantum computation and cryptography on a chip. We engineer the phase velocity of the fundamental quasi-TM mode of the silicon ring microresonator to meet the group velocity of electrons in an SEM. This phase-matching condition allows tuning the wavelength of the emitted photon by adjusting the energy of the passing electron. Thus, in the range of electron energies from 20 to 30 keV, available in most SEMs, multi-octave tuning of emitted photons in the telecom wavelength range is possible from 1 µm to more than 3 µm.

The use of SEMs instead of TEMs simplifies and reduces the cost of the experiments, allows the use of high-aperture optics inside spacious and easily configurable experimental chambers. Together with this, the high efficiency of electron detection, the generation of photons directly into the photonic microresonator, and broadband tunability make this approach a promising source of quantum states of light.

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Dionisis Stefanatos, *University of Patras (Greece)*
Optimal shortcuts of stimulated Raman adiabatic passage in the presence of dissipation

Abstract:
We use optimal control theory to obtain shortcuts to adiabaticity which maximize population transfer in a three-level stimulated Raman adiabatic passage (STIRAP) system, for a given finite duration of the process and a specified dissipation rate of the intermediate excited state. We fix the sum of intensities of the pump and Stokes pulses and use the mixing angle of the fields as the sole control variable. We determine the optimal variation of this angle using numerical optimal control and reveal the role of the singular arc in the optimal trajectory, so the effect of dissipation is minimized [1]. In order to find approximate analytical expressions for the impulses, the durations of the zero control intervals and the singular control, which are the elements composing the optimal pulse sequence, we use the spin to spring mapping [2] to formulate the corresponding optimal control problem on the simpler system of a classical driven dissipative harmonic oscillator, which we subsequently solve [3]. We also derive suboptimal solutions for the spring problem, one with less impulses than the optimal and others with smoother polynomial controls. We then apply the solutions derived for the spring system to the original spin (STIRAP) system and compare the population transfer efficiency with that obtained for the original system [1]. For all dissipation rates used, the efficiency of the optimal spring control approaches that of the numerical optimal solution for longer durations. The efficiency of suboptimal spring control with less impulses is very close to that of the optimal spring control in all cases, while that of polynomial controls lies below, and this is the price paid for not using impulses, which can quickly build a nonzero population in the intermediate state. The present optimal solution for the classical driven dissipative oscillator can also be applied in the transport of a coherent state trapped in a moving harmonic potential and of a mesoscopic object in stochastic thermodynamics.

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Jannik Ströhle, *Ulm University - Institut of Quantum Physics (Germany*)
Dimensional reduction in cavity QED and the light-matter-interaction

Abstract:
Performing experiments with atoms in cavity QED setups has advantages for a multitude of reasons when comparing to free-space settings; for instance power enhancement, more precise spatial filtering and more accurate beam profiles. From the theoretical side, a number of quantum optical approximations can also be applied to simplify the computations. One of those approximation is the dimensional reduction, i.e. treating a three-dimensional cavity as a one-dimensional problem. This is usually justified by having one length of the cavity much larger than the remaining ones, and is usually done in an ad hoc fashion without a derivation from first principles.
Starting from the Helmholtz equation, we show how to rigorously obtain a lower-dimensional model from 3D cavity QED for general cavity geometries that are separable in its longitudinal and transverse degrees of freedom. This is an extension to an already existing theory, where this problem has been studied with a scalar version of the atom-light interaction. Here, however, we actively account for the vector nature of electromagnetism. In the process, the electric and magnetic fields decompose into an infinite collection of vector-valued subfields which live on the remaining single dimension but encode geometrical information of the cavity in the other two spatial dimensions. This procedure naturally extends to

any light-matter interaction terms included in the theory, such as due to laser beams. A dimensional reduction approximation can then be obtained via a single-mode or few-mode approximation on those subfields. Due to corrections that arise from the higher-dimensional theory, it is generally not equivalent to the usual way of prescribing this approximation ad hoc. This is in particular true in the common regime of having a very long but narrow cavity. Finally, we show when this modified dimensional reduction is valid, i.e. in which regimes a single or a few subfields are sufficient to reconstruct the full 3D dynamics.

Vitaliy Sultanov, *FAU Erlangen-Nürnberg (Germany)*

Time-resolved distillation of photon pairs from ultrasmall sources

Abstract:
Miniaturized sources of quantum photonic states are in the spotlight of research due to their great potential for investigating light-matter interaction at the nanoscale and realizing quantum technologies with integrated photonic circuits. They provide unprecedented freedom in quantum state engineering and feature multifunctionality combining the action of quantum light generation and quantum state shaping. One of the prospective directions is photon pair generation via spontaneous parametric down-conversion (SPDC) from ultrasmall sources like thin films, metasurfaces, or nanoantennas. However, a fundamental problem here is the contamination of generated two-photon light with thermal radiation caused by photoluminescence. As the source gets smaller, the role of photoluminescence increases, and the thermal background starts to prevail. Photoluminescence cannot be filtered out spectrally or spatially as it is emitted in a broad angular-frequency range overlapping with generated photon pairs.
In this work, we propose and implement a solution to this problem. It is based on the fact that SPDC, in contrast to photoluminescence, is a parametric process with almost instantaneous response. Through time-resolved measurements, we distill the quantum state of photon pairs generated from a 6.5 um thick layer of lithium niobate and drastically reduce the level of thermal noise. We characterize the quality of the generated photon pairs by the quantity known as the heralding efficiency. A direct measurement leads to a heralding efficiency of 0.08%, which is an extremely low value but typical for miniaturized two-photon sources. By applying time-resolved distillation, we reduce thermal background noise by two orders of magnitude and increase the heralding efficiency to 9.6%, which corresponds to the source heralding efficiency of about 90% after correction for the detection efficiency. The reduction of the intrinsic noise makes miniaturized two-photon sources of photon pairs budding for the generation of highly-dimensional entangled two-photon states of high purity. We observe an ultrabroad spectrum of generated photon pairs pointing towards a high degree of entanglement in frequency. Moreover, we demonstrate the generation of photon pairs via different types of SPDC occurring simultaneously, which is impossible in bulk crystals. This feature gives another degree of freedom for the two-photon polarization state engineering.

Towsif Taher, *University of Geneva (Switzerland)*

Enabling optical quantum technologies with high-speed photon number resolving snspd array

Abstract:
Fast, efficient and precise single photon detection is crucial for most quantum optics experiments. Superconducting nanowire single-photon detectors (SNSPDs), thanks to their high detection efficiency, exceptionally low dark counts, and fast recovery time, have set the benchmark for detectors in this field. However, the widespread use of applications such as linear optical quantum computing (LOQC), gaussian boson sampling, quasi-deterministic heralded single-photon sources, and quantum repeaters would require high-speed detectors that are also able to distinguish different photon number states in various forms of quantum light. To achieve photon number resolving (PNR) capability with SNSPDs, spatially multiplexed SNSPDs connected in series or parallel and temporal multiplexing of SNSPDs have been demonstrated.

However, these multiplexed SNSPDs can only resolve photon numbers for light pulses with a duration of up to a few hundred picoseconds and are limited in the maximum detection rate achievable. Here, we present a superconducting nanowire single-photon detector array composed of 14 independent pixels that simultaneously deliver high performance in terms of system detection efficiency (SDE), jitter, recovery time, and maximum count rate while showing dynamic, i.e., with no limitation on the coherence time of the photons, PNR capability. The detector demonstrates a maximum system detection efficiency (SDE) of 90% in the telecom band, less than 6 ns single-pixel recovery time, and an average single-pixel jitter of ~20 ps. By reading each pixel independently, we show that the SNSPD array can operate at an unprecedented speed, detecting telecom photons at 1.5 Gcps with 45% absolute SDE while maintaining above 80% SDE up to 400 Mcps. We show how a similar array that we fabricated and characterized has been exploited to demonstrate quantum key distribution (QKD) with secret key rates exceeding 60 Mbps over a distance of 10 km. Furthermore, we exploit the dynamic PNR of the array to demonstrate accurate state reconstruction for different photon-number statistics for a wide range of light inputs; imitating operation with photons with long coherence times, such as photons obtained from cavity-enhanced SPDC or SFWM, used for quantum communication or squeezed light generation. We show 2-photon and 3-photon state fidelity of 74% and 57%, respectively, representing state-of-the-art results for fiber-coupled SNSPDs. Such detectors could find immediate use in LOQC protocols where the capability to distinguish few photons is sufficient. Our work expands the frontiers of what is currently achievable with SNSPDs and would help advance numerous quantum photonics applications.

Kan Takase, *the University of Tokyo (Japan)*

Gottesman-Kitaev-Preskill qubit synthesizer for propagating light

Abstract:
Practical quantum computing requires robust encoding of logical qubits in physical systems to protect fragile quantum information. In terms of scalability, using Bosonic modes is a promising approach because each logical qubits can be encoded in just one Bosonic mode. A prime example of such encoding is Gottesman-Kitaev-Preskill (GKP) scheme [1]. Given GKP qubits and ancillary magic states, which is GKP qubits with a special superposition coefficient, fault-tolerant and universal quantum computing is possible using only Gaussian operations.

Quantum computation using GKP qubits can be defined in any type of quantum harmonic oscillator, but the challenges for its realization vary greatly depending on the physical system. Although it is relatively easy to generate GKP qubits in nonlinear systems such as trapped ions and superconducting circuits, interacting the generated qubits for quantum computing is difficult. In contrast, in propagating light, GKP qubits are difficult to generate due to weak nonlinearity but easy to use. A scalable platform that can input multiple GKP qubits and perform arbitrary Gaussian operations has already been demonstrated [2]. Therefore, generation of GKP qubits in propagating light is one of the most desired breakthroughs for realizing practical quantum computers.

Here, we propose a synthesizer that encodes Gottesman-Kitaev-Preskill (GKP) qubits in propagating light, which is based on a novel formulation to exploit the nonlinearity of photon detectors for discretizing and periodizing a wavefunction of a Bosonic mode. This synthesizer has four advantages: (i) systematic and rigorous synthesis of arbitrary superpositions of GKP qubits, (ii) requires minimal resources, (iii) high fidelity and high success probability, and (iv) robustness against loss. As an example, I1_L> qubit with 10 dB squeezing and more than 0.99 fidelity can be generated from a circuit consists of four squeezed vacuum states, three beam splitters, and three photon number resolving detectors. The actual parameters of all these elements are determined easily according to our formulation. From the consideration of photon loss and success probability, it is estimated that generation of GKP qubits with 7 dB squeezing is possible by using existing devices, and even the practical level of 10 dB is realistic in the future. This result fills an important missing piece toward practical quantum computing.

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Benedict Tohermes, *ILP, University of Hamburg (Germany)*

High bandwidth two-mode squeezed states for continuous variable quantum key distribution

Abstract:
Practical quantum computing requires robust encoding of logical qubits in physical systems to protect fragile quantum information. In terms of scalability, using Bosonic modes is a promising approach because each logical qubits can be encoded in just one Bosonic mode. A prime example of such encoding is Gottesman-Kitaev-Preskill (GKP) scheme [1]. Given GKP qubits and ancillary magic states, which is GKP qubits with a special superposition coefficient, fault-tolerant and universal quantum computing is possible using only Gaussian operations.

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[2] W. Asavanant et al., Science 366, 373 (2019).

Dániel Varga, *Wigner Research Centre for Physics (Hungary)*

How to load cold atoms into an intra-cavity dipole trap and use said cavity to count the atoms in the trap

Abstract:
We demonstrate dipole trapping of a cold ensemble of atoms within a single mode of a high-Q optical cavity in the collective strong coupling regime, using a far detuned light source.
The atoms, previously collected in a MOT, are transported magnetically between the cavity mirrors, where they are transferred to an intra-caity dipole potential. The lifetime of the trap is several hundreds of

milliseconds. The momentary atom number can be monitored, by a second, weak probe light, close to the atomic resonance. Unfortunately this probe can also pump the atoms into an uncoupled ground state. State independent trapping of the atoms becomes possible, by adding a third light at a specific frequency, that can repump the atoms from the uncoupled ground state.

Chloé Vernière, *Sorbonne Université - Institut des Nanosciences de Paris (France*)

Encoding images in quantum correlations of photons

Abstract:
Quantum entanglement is a key property that allows to transmit information in a secure way. In this respect, entangled photons correlations can be used to carry information that classical intensity measurements cannot reveal. In this work, I explore the possibility of encoding and retrieving information in the second order correlations of spatially-entangled photon pairs produced by type-I spontaneous parametric down conversion in a non-linear crystal. For that, I use wavefront shaping combined with phase retrieval algorithms to deterministically shape photon correlations and thus encode information, for example under the form of an image. After propagation, photons are detected using an Electron Multiplier Charge-Coupled Device camera to reveal the correlation-encoded image. This information remains undetectable for intensity measurements. In the same perspective, instead of using wavefront shaping, the image of a real object can also be encoded in the photons correlations by directly imaging its Fourier transform onto the crystal. Photon pairs are thus only generated at positions corresponding to the Fourier transform of the object, which then appears in the correlation measurements. Our approach enables the transmission of complex, high-dimensional information using in quantum correlations of photons, which can be useful for developing quantum communication and imaging protocols.

Alejandro Vivas-Viaña, *Universidad Autónoma de Madrid, Madrid, (Spain)*

Unconventional mechanism of virtual-state population through dissipation

Abstract:
The definition of a virtual state requires that the probability of finding the system in such state should be vanishingly small, since time-energy uncertainty only allows it to exist for an extremely short time [1]. An extremely relevant quantum-optical scenario described in terms of virtual states consists of two quasi-resonant “real” quantum states, whose interaction is mediated by a third, strongly off-resonant “virtual” state. In this work, we study such a system in a specific dissipative context in which spontaneous decay occurs only between the real states, and show that the situation where the virtual state is unpopulated is, in fact, metastable [2]. In stark contrast to common intuition, we show that there is a steady-state reached in the long-time limit where the virtual state acquires a sizable population. We analyze this phenomenon from the perspective of quantum trajectories, and show that this unconventional population mechanism stems from the non-Hermitian evolution taking place between quantum jumps. Introducing a novel hierarchical scheme of adiabatic elimination, we obtain analytical expressions for the dynamics and the timescale of metastability that describes for how long the virtual state remains, indeed, virtual [3].

These results are relevant for the design of interacting quantum systems via artificial environments and their possible application for quantum technologies, such as entanglement generation mediated by photonic structures in dissipative scenarios [4,5]. We apply our findings to demonstrate a novel mechanism for the generation of high degree of entanglement between two nonidentical qubits when they are both driven at the two-photon resonance [6].

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Yuma Watanabe*, ICFO – The Institute of Photonic Sciences (Spain)*
The DMRG study on the two-band extended Bose-Hubbard model

Abstract:
Bosonic particles in lattices provide a fertile platform for studying strongly-correlated systems and have high experimental feasibility due to their exceptional controllability. The Bose-Hubbard (BH) model describes bosonic particles in lattices and has been extensively studied theoretically and experimentally. Many kinds of generalized BH models effectively describing interacting bosons in a single band have been widely explored theoretically, taking into account the additional terms, e.g. nearest neighbor interactions, has led to various novel phases such as so-called supersolids. Experimentally, despite many excellent results in the case of short-range interactions, it remains challenging to realize systems with long-range interactions. However, a recent study has reported that the checkerboard, one of the lattice symmetry broken phases induced by nearest-neighbor interactions, can be realized with dipolar excitons in two-dimensional square lattice potential, which can be described in terms of the multi-band Bose-Hubbard models. This research opens up the possibilities of experimentally realizing novel phenomena in multi-band Bose systems with long-range interaction.

Here, we, therefore, study the two-band extended Bose-Hubbard model. In particular, we investigate the ground states in the one-dimensional system using the density matrix renormalization group (DMRG) method. To find phases induced by inter-band interactions, we first fix the particle numbers in each band to unit-filling independently. We find that by starting in independent bands supporting a superfluid in one band, and density wave or Haldane insulator in the other, interactions induce a supersolid state in the former of these bands. Revealingly, setting both band parameters to obtain superfluid ground states in the case of uncoupled bands, interband interactions are shown to lead to the so-called Haldane superfluid characterized by both superfluidity and non-local string order. Finally, we will also discuss the effect of a non-zero band energy gap where only the total particle number in the system is conserved.

Mingzhu Weng, *Northeast Normal University (China)*
Giant atoms interaction and entanglement induced by coupled resonator waveguide

Abstract:
We investigate the interaction between giant atom array in a coupled resonator waveguide, where two kinds of giant atoms are arranged alternately. By regulating the distance between the two atom-waveguide coupling sites, we find that there are three different effective (dissipative) coupling types. For the two giant atoms setup, we tomography the steady-state and its entanglement. We find that the resonant driving will induce a considerable entanglement and the entanglement is manifested as a Rabi splitting character. For an array of giant atoms, we study the entanglement between arbitrary two atoms and find a nonmonotonic

behavior of the concurrence and a function of atomic distance. We hope these controllable interactions between giant atoms are of great applications in quantum information processing.

Batuhan Yilmaz, *University of Toronto (Canada)*
Generating a 4-photon "tetrahedron" state: towards simultaneous super-sensitivity to non-commuting rotations

Abstract:
One of the primary goals of quantum metrology is to understand the optimal way to measure multiple incompatible observables. A common misconception in multiparameter estimation was that the high sensitivity of a quantum state to a particular transformation comes with the cost of decreased sensitivity to other transformations generated by different non-commuting observables; this was disproved by the introduction of the "compass state", which is sensitive to measurements in both position and momentum displacement. For SU(2) rotations, there exists a similar group of states that are equally supersensitive to rotations around any axis, are second-order unpolarized, and can possess the rotational properties of platonic solids in particular dimensions. Here, we report on the experimental demonstration and characterization of the lowest-dimensional state belonging to this class, a four photon state which we call the "tetrahedron state" due to its tetrahedral symmetry.
The tetrahedron state, which we generate from a three-photon N00N state and an additional single photon, is an analogue of the compass state created in the symmetric subspace of the polarization of four optical photons, and is the optimal state for simultaneous estimation of all parameters describing a rotation. We investigate the ability of the tetrahedron state to simultaneously measure all parameters of a rotation and compare the results with those obtained using different strategies, such as using spin-coherent states and N00N states.

Chengsong Zhao, *School of Physics, Dalian University of Technology (China)*
Dissipative-coupling-induced transparency and high-order sidebands with Kerr nonlinearity in a cavity-magnonics system

Abstract:
The dissipative coupling in cavity magnonics provides a new way to exploit dissipation to achieve quantum tasks. In this work, we investigate dissipative-coupling-induced transparency (DCIT) and high-order sideband generation in a dissipative photon-magnon coupling system. We find that DCIT can occur in both weak and strong driving fields and that the high-order sidebands can be enhanced greatly by optimizing the system parameters. Specifically, we find that the first- and second-order sidebands can be enhanced significantly near the exceptional points of the effective Hamiltonian and that the enhancement of sidebands reaches its maximum values near the critical point of the stability region. Our results demonstrate the potential application of dissipative photon-magnon coupling systems for quantum information processing and optical communications.

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Wei Zhao, *Northeast Normal University (China)*

Single photon scattering on a giant atom within waveguide QED setup

Abstract:
We investigate the single-photon scattering in a 1D coupled-resonator waveguide and linear waveguide setup. For the coupled-resonator waveguide, we find that the interference effect will lead to a Breit-Wigner or Fano lineshape for the reflection rate, depending on the size of the giant atom. We further demonstrate the bound state phase transition and reveal the linear scaling for the critical coupling strength as a function of the atomic size. For the linear waveguide, we find that the interference effect between different atomic transition paths can lead to a complete transmission window, analogous to Autler–Townes splitting (ATS), and the width of the transmission valley (reflection range) is tunable in terms of the atomic size. These results can be further understood in the viewpoint of quantum open system. Our results show that, the size of the giant atom, which plays as a new degree of freedom, is potentially applicable in the designing and manipulating of coherent photon device.