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Quantum 2017

From Foundations of Quantum Mechanics to Quantum Information and Quantum Metrology & Sensing

Rectorate of the University of Torino (Italy), 7-13 May 2017

Quantum 2017 will be the eighth edition of this international conference attended by researchers coming from all over the world. Purpose of this workshop is to favour the exchange of ideas and discussion on last results among leading physicists working in the interconnected fields of Quantum Metrology- Sensing & Imaging, Quantum Information and Foundations of Quantum Mechanics, in particular in the framework of quantum optics. It is organized ad memoriam of our colleague and friend Carlo Novero who gave birth to this experimental research line in Turin.

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Optimal continuous variable teleportation of coherent states with finite entanglement

Gerardo Adesso

We consider quantum teleportation of ensembles of coherent states of light with a Gaussian distributed displacement in phase space.
We address the following general question: given a certain amount of entanglement available as a resource, what is the maximal fidelity that can be achieved on average in the teleportation of such an ensemble of states?
We answer the question analytically by means of an optimisation within the space of Gaussian quantum channels, which allows for an intuitive visualisation of the problem.
We first show that not all channels are accessible with a finite degree of entanglement, and then prove that practical schemes relying on non symmetric entangled states (i.e., unbalanced twin beams) enable one to reach the maximal fidelity at the border with the inaccessible region. If time permits, we also discuss the optimal teleportation protocol at fixed degree of steering.
In general, the optimal schemes we find can be readily implemented experimentally by a conventional Braunstein-Kimble teleportation protocol involving homodyne detections and corrective displacements with an optimally tuned gain.
These protocols can be integrated as elementary building blocks in quantum networks, for robust storage and transmission of quantum optical states.

Conditional Hybrid Nonclassicality

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We provide a general method to characterize the nonclassicality in compound discrete- and continuous-variable systems. For this purpose, we introduce the operational notion of conditional hybrid nonclassicality which relates to the ability to produce a nonclassical continuous-variable state by projecting onto a general superposition of discrete variable states. This form of quantumness is particularly important in connection with interfaces for quantum communication. To verify the conditional hybrid nonclassicality, a matrix version of a nonclassicality quasiprobability (NQP) is derived. The NQPs are regularized versions of the highly singular Glauber-Sudarshan P-function [1]. They show negativities for any nonclassical state and can be directly obtained from experimental data. Multipartite quantum correlations (QC) of light are revealed by using NQPs, which are necessary and sufficient to visualize any multipartite QC [2]. This direct sampling of NQPs is a powerful and universal method to verify quantum effects of arbitrary quantum states. To show the strength of our method in the hybrid scenario, we experimentally generate an entangled Schrödinger cat state, using a coherent photon-addition process acting on two temporal modes, and we directly sample its NQP matrix [3]. The considered types of quantum effects are certified with high statistical significance.

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Non-trivial structures in very intense twin beam states
Alessia Allevi

We present the results of a recent experiment aimed at investigating the spatio-spectral properties of parametric down-conversion (PDC) in different intensity regimes and with a set of BBO crystals having different lengths. The experimental setup was based on an imaging spectrometer combined with either a photon-number resolving (PNR) detector or an electron-multiplying (EMCCD) camera.
The PNR detector, preceded by a set of neutral density filters to explore the different intensity regimes, allowed us to reconstruct the statistics of detected photons inside a single spatio-spectral area, by evaluating the intensity auto-correlation function.
We noticed that the evolution of the number of modes and that of the mean number of photons inside one area as functions of pump power are similar for all the analyzed crystals. In particular, for all of them, we recognized the presence of a minimum in the number of modes and a change in the slope of the mean number of photons, whose growth is described by sinh^2 for lower pump powers and by a nearly linear function for high values.
However, the dynamics of the PDC process as a function of pump power is faster in the case of long crystals than for short crystals, probably also because of the walk-off effect.
At variance with the PNR detector, the EMCCD camera, being it endowed with spatial resolution, was used to study the behavior of the spatio-spectral cross-correlation areas as a function of pump power and of the length of the crystals. On this side, we noticed that at high pump powers the correlation areas acquire an additional spectral structure, especially in the case of long crystals. In more detail, thanks to the high spectral resolution (0.03 nm) of the detection apparatus (imaging spectrometer + camera), we observed that more than one compact spatio-spectral cross-correlation area, endowed with different spectral components, correspond to the same autocorrelation area. This effect reduces the strength of the cross-correlation peak and hence testifies the degradation of the level of correlations between signal and idler. The break-up of the cross-correlation areas into more-than-one component can be ascribed to the spatio-spectral modification of the pump, which cannot be considered un-depleted for high pump powers.
These results manifest a non-trivial spatio-spectral structure in the high-intensity regime.

Probing quantum-spacetime structure with GRB photons and neutrinos

Giovanni Amelino-Camelia

For nearly two decades the possibility of probing short-distance spacetime structure using photons and neutrinos from gamma-ray bursters has been among the most studied in quantum-gravity research.
Recently the quality of available data is much improved, and I here give an overview of these developments.
Intriguingly, the present data situation, while inconclusive, lends itself to interpretation in terms of dispersive propagation in a quantum spacetime.

Squeezed light enhanced sensing and cooling of a micro-mechanical oscillator

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Ultra-precise measurements of various parameters such as the mass of nano-particles, magnetic fields or gravity can be attained by probing the phononic modes of a micro-mechanical oscillator with light. In such a measurement, the sensitivity is partly governed by the noise of the phononic mode as well as the noise of the probing light mode. Therefore, by reducing the noise of the probe beam an enhanced sensitivity can be expected.

We demonstrate this effect by using squeezed states of light where the quantum uncertainty of the relevant quadrature is reduced below the shot noise level. Using this squeezing-enhanced sensitivity effect, we demonstrate 1) improved feedback cooling of a phononic mode in a microtoroidal cavity [1] and 2) improved sensing of a magnetic field using the coupling to a microtoroidal phononic mode via a magnetorestrictive material. We present our recent experimental results and discuss future directions.

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Witnessing the metrological efficiency with few expectation values

Iagoba Apellaniz

Abstract. In quantum metrology, the precision of parameter estimation plays a central role. For a given quantum state, the quantum Fisher information characterizes the best achievable precision, hence it is very important to obtain it in an experiment. We show how to estimate the quantum Fisher information as a figure of merit of metrological usefulness based on a few expectation values. Our approach is optimal since it gives a tight lower bound on the quantum Fisher information for the given incomplete information. We apply our method to the results of various multi-particle quantum states prepared in experiments with photons, trapped-ions and cold atomic ensembles, such as spin-squeezed states and Dicke states. Based on a few operator expectation values, our approach can also be used for detecting and quantifying entanglement in very large systems.

Co-authors. Matthias Kleinmann, Otfried Ghne and Gza Th

Quantum Structure of Spacetime

P. Aschieri

Spacetime texture at Planck scale is a main theoretical and experimental challenge. Its discretized and noncommutative geometry structure emerges in different quantum gravity models.

We outline how noncommutative geometry provides a general framework where to consistently describe dynamics in such quantum spacetimes and suggests models (e.g. wave equations with modified dispersion relations) to be tested experimentally.

Quantum measurement in weak coupling regime: from non-contextuality in weak values to protective measurements

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Quantum mechanics, one of the keystones of modern physics, has an unprecedented success in predicting the behavior of nature, leading to a perfect agreement between theoretical predictions and experimental results in a vast amount of fields. However, until this day, there is a strong debate about the foundational concepts of quantum mechanics [1-4].

Weak value measurements have recently given rise to a great amount of interest in both the possibility of measurement amplification and the chance for further quantum mechanics foundations investigation.

In particular, a question emerged about weak values being proof of the incompatibility between quantum mechanics and non-contextual hidden variables theories (NCHVTs). A test to provide a conclusive answer to this question was given by Pusey [5] where a theorem was derived showing the NCHVT incompatibility with the observation of anomalous weak values under specific conditions. We realized this proposal, clearly pointing out the connection between weak values and the contextual nature of quantum mechanics [6].

Another very intriguing aspect of quantum mechanics that we have investigated by means of weak measurements is the fact that variables might not have definite values. A complete quantum description provides only probabilities to obtain various eigenvalues of a quantum variable. In particular, the expectation value is known to be a statistical property of an ensemble of quantum systems. In contrast to this paradigm, we demonstrate a unique method allowing to extract information about the expectation value of a physical variable on a single particle with a single measure. Our experimental implementation corresponds to the first realization of the quantum protective measurement [7].

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Coherent Control of Atomic q-bits by Non-classical Light and Phase Measurements

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The interaction of non-classical electromagnetic field with atoms is a very important and interesting problem of modern quantum optics and laser physics. One of the most promising applications concerns the quantum information and quantum computing purposes: to store the quantum information and to produce the needed quantum state "on demand" becomes of great importance [1, 2]. The most difficult problem in this case is to provide a coherent control of atomic q-bits and to transfer the phase information between the field and the q-bit providing an interface between the field and atomic subsystems. To use and record the phase seems to be the main advantage of the quantum information protocols in comparison to the classical ones and can strongly enlarge the information capacity.

One of the possible ways to encode the quantum information is to use few-photon coherent states with different phases. However if the mean number of photons is small there is a problem to distinguish different states with rather close phases. In this work we investigate the interaction of few-photon non-classical states of light with an atomic q-bit. Method to transfer the phase from the superposition of quantum photon states to atomic q-bit is suggested. A simple way to measure the value of the transferred phase is demonstrated. The possibility to distinguish few-photon coherent states with close phases due to their interaction with atomic q-bit is discussed.

Instead of usually used two-level atomic model we consider a model Rydberg atom which is characterized by several bound levels and the continuum and allows the investigation of both the field-induced ionization and excitation of the atom including the repopulation of highly excited atomic states by both Lambda (via the continuum) and V transitions (via the low-lying resonant state). The interacting quantum field is supposed to be initially in a superposition of several Fock states with some relative phases. The interaction between the considered atomic system and non-classical light is investigated analytically by solving the time-dependent Schrödinger equation using the quasienergy approach [3]. The ionization and stabilization of the atomic system is investigated. The role of entanglement between the atomic and the quantum system during the interaction is examined. The possible transfer of the phase from the quantum field state to the atomic q-bit is demonstrated. The way to control the phase transfer procedure in experiment by ionization measurements is suggested. The possibility to distinguish few-photon coherent states with different phases is analyzed in dependence on the phase uncertainty and mean number of photons.

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Noisy evolution of coherent states in a lossy Kerr medium

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Using the general solution for a damped nonlinear oscillator, we identify the excess noise arising in the evolution of a coherent light pulse subjected simultaneously to Kerr self-phase modulation and linear attenuation. This noise is shown to limit the useful signal power in communication schemes based on phase shift keying.

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Strategies for multiparameter estimation.

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The interaction of light with a system can deliver meaningful information on the characteristics of the sample: rarely, however, all the information can be contained in a single parameter. Assessment of multiple quantities may be needed, being them linked to either unitary (i.e. phases) or dissipative processes (i.e. dephasing). In this talk we will review some recent results on the ability - or lack thereof - of quantum metrology to deliver an enhancement in the simultaneous estimation of multiple parameters. In particular, we will discuss the role of entangling measurements for the joint monitoring of phase and dephasing. We will also illustrate a method for inspecting complicated measurements without recurring to quantum detector tomography.

Wave function collapse and gravity

Angelo Bassi

Abstract: To make quantum theory consistent, models of spontaneous wave function collapse (collapse models) propose to modify the Schrödinger equation by including nonlinear and stochastic terms, which describe the collapse of the wave function in space. These spontaneous collapses are rare for microscopic systems, hence their quantum properties are left almost unaltered.

At the same time, since the collapses add coherently in composite systems, macroscopic spatial superpositions of macro-objects are rapidly suppressed. I will review the main features of collapse models.

In particular, I will discuss ideas to connect the collapse of the wave function to gravity: The Diosi-Penrose model, Adler’s model and the Schroedinger-Newton equation.

Next, I will present an update of the most promising ways of testing them in interferometric and non-interferometric experiments, showing the current lower and upper bounds on their parameters.

Coherent control of silicon-vacancy centers in diamond

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Full coherent control of quantum systems is a key prerequisite to build a quantum information processing (QIP) system. Spatially selective and ultrafast control of individual qubits in multi-qubit systems, on the other hand, optimally is based on all-optical control techniques using short laser pulses. However, these techniques require optically accessible quantum systems with suitable electronic level configurations to allow for the application of ultrafast and thus broadband pulses. Furthermore, to enable good scalability, quantum systems in the solid state are generally preferred. We here show that silicon vacancy centers (SiV) in diamond are ideal systems for all-optical coherent control.

The negatively charged SiV center in diamond features an advantageous electronic structure and superior spectral properties [1]: At liquid helium temperatures, the SiV exhibits a narrow zero phonon line with a four-line fine structure and lifetime-limited linewidths on the order of 120MHz [2]. Furthermore, due to its small Huang-Rhys factor, up to 80% of the fluorescence is emitted via these zero-phonon line transitions with only small contributions from phonon sidebands. Moreover, the SiV offers an optically accessible Λ-type level structure with a large orbital level splitting and previous studies determined the ground state coherence time of the center to be on the order of 35-45ns at a temperature of 4K [3].

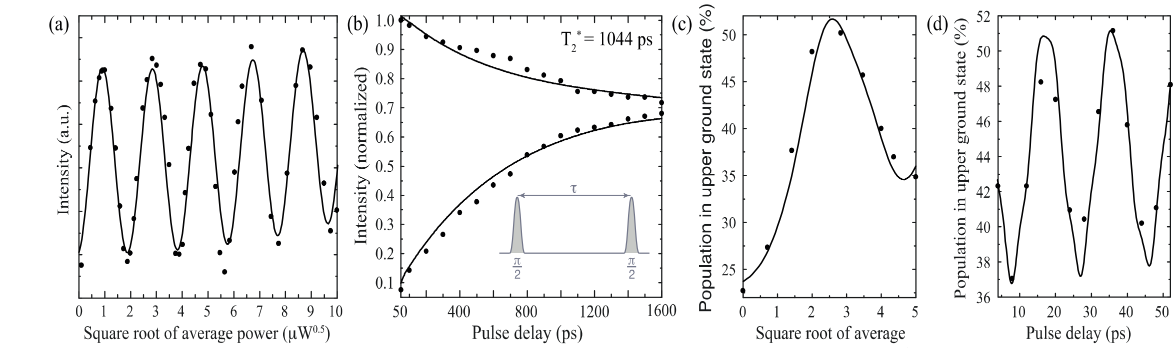

Fig. 1 Resonant Rabi oscillations (a) and Ramsey interference (b) demonstrate full coherent control of a single SiV using 12ps long laser pulses. Moreover, applying off-resonant 1ps laser pulses enable full ground state control via Raman-based Rabi oscillations (c) and Ramsey interference (black dots are measured data, solid black lines show simulations via a density matrix model).

We here report on all-optical resonant coherent control via Rabi oscillations (Fig 1(a)) and Ramsey interference (Fig 1(b)) of the orbital degree of freedom of the SiV [4]. Moreover, we extend these techniques to a Raman-based control scheme (Fig 1(c,d)) which allows harnessing the full ground state coherence of the SiV by performing coherent rotations solely within the ground state manifold of the center, rendering the SiV promising as a qubit in future QIP applications. We further demonstrate that the SiV spin states can be coherently controlled by microwave radiation. Eventually, we discuss techniques for extending the coherence time by cooling and phonon engineering as well as potential applications of SiV ensembles in Raman-based quantum memory schemes.

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Measurement-induced quantum state engineering and emulation of strong optical nonlinearities

M. Bellini, L.S. Costanzo, N. Biagi, A.S. Coelho, J. Fiurasek, C. Hughes, M. S. Kim, A. Zavatta

We perform conditional quantum operations on weak states of light in order to implement highly non-trivial state transformations. Coherently combining sequences of single photon additions and subtractions allows us to orthogonalize any input light state and to generate coherent superpositions of the input and output states, thus producing arbitrary continuous-variable qubits.
Furthermore, we show that the appropriate combination of the above elementary quantum operations can faithfully emulate the effect of a strong Kerr nonlinearity on weak states of light. We experimentally demonstrate a nonlinear phase shift at the single-photon level by using weak coherent states as probes and characterizing the output non-Gaussian states with quantum state tomography.
Both the generation of arbitrary continuous-variable qubits and the emulation of strong Kerr nonlinearities at the single-photon level represent crucial enabling tools for optical quantum technologies and for advanced quantum information processing.

Quantum coherent transport in a three-arm superconducting beam splitter

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In the last decade, research on physical implementations of quantum bits (qubits) has achieved a series of remarkable results. In a large quantum system, many spatially separated nodes storing qubits may interact and communicate across a network [1] and to provide the speedup of the information transportation, it would be beneficial to support the transmissions of entangled qubits [2]. Although at the moment photons seem to represent the best qubit carrier for fast and reliable communication over long distances, solid-state (first of all, superconducting) technologies have better prospects for scalability and could provide more ingenious ways to link a lot of qubits and quantum gates.

Recent developments of electron quantum optics [3], a novel platform aiming to study the behavior of electrons in ballistic quantum conductors using paradigms and methods of quantum optics, have given us new ways to probe the behavior of electrons in quantum conductors. In this contribution, we propose to use this approach for characterizing the coherent maintenance in a simple superconducting (S) device, a hybrid fork with two S terminals and a normal (N) counter-electrode coupled to them. We suppose that the distance d between the two NS connections is less than the phase decoherence length L_Φ in the N metal. The fully quantum treatment of the problem requires continuity of the wave function and the probability flux conservation at the contact point. It follows that the backscattering in the three-arm structure takes place even without any scattering at the node and for identical leads, and thus the current through the system can be strongly modified comparing to the 'trivial' case of $d > L_\Phi$ when the total transmission probability is a sum of partial contributions for NS transferring events. If the scattering effect at the node is nonzero, the conductance spectrum is more like a 'trivial' result for two parallel tunneling junctions with the only but significant difference that, in the first case, we have independent weighting factors while, in the consistent quantum theory, the only fitting parameter determines the shape of the conductance spectrum. Introduction of a decoherence amount at the device node restores the 'trivial' results.

Resuming, our results pave the way towards experiments establishing the presence and amount of quantum entanglement in superconducting interconnects as well as an estimation of the phase decoherence length in quantum networks. Recent progress in the fabrication of ultra-thin metallic lines with favorable characteristics permits to focus the analysis on the ballistic limit employing the notion of semiclassical electron trajectories and treating thus the problem exactly and comprehensibly.

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Complementarity in multi-path interferometers

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Abstract

A particle going through an interferometer can exhibit wave or particle properties. In a seminal study of the two-path interferometer, Englert [1] introduced detectors into the problem and defined the path information, D, as the discrimination probability of the detector states. He derived a relation between this type of path information and the visibility V of the interference pattern, in the form

$$D^2 + V^2 \leq 1. \tag{1}$$

This was later generalized to multi-path interferometers [2, 3]. However, in all of these works an l_2 measure of coherence was employed. The results, therefore, are relations between second moments and, thus, closely related to uncertainty relations.

Recently a theory of quantum coherence as a resource for quantum information processing was proposed along with two possible coherence measures, an entropic measure and an l_1 measure [4]. Bera, *et al.* derived a relation between path information and coherence based on the l_1 measure [5]. They used unambiguous discrimination for distinguishing the detector states and found a relation in the form of a *linear* sum, $D + V \leq 1$. This is clearly not of the form given in Eq. (1). Furthermore, unambiguous discrimination is not possible when the detector states are linearly dependent. In the derivation of Eq. (1), minimum-error state discrimination was employed, which is always possible, even if the detector states are linearly dependent. The probability of successfully identifying the detector states quantifies the available path information.

In our recent work [6] we derived a duality relation for multi-path interferometers in the form of Eq. (1) based on the l_1 coherence measure and an independent one based on the entropic coherence measure. Here we give an overview of these results and present a family of new duality inequalities that explicitly depend on the number of paths and are sharper than the one given in Eq. (1). Some of our predictions have been verified experimentally in recent tests of complementarity [7] and [8].

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Toward Nitrogen Vacancy Center based Scanning Near Field Microscopy

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In the last years, the superior stability of individual nitrogen vacancy (NV) color centers in diamond as dipole emitters triggered several efforts to realize a near field microscope based on NV centers e.g. [1]. In recent attempts, a nano-diamond (ND) placed close to the apex of a commercial AFM tip was approached to a surface covered with a dye layer or with graphene flakes [1]. The NV centers and the dye-molecule/graphene flake form a Förster Resonance Energy Transfer (FRET) pair and the spatial resolution potentially reaches the FRET radius (<10 nm for NV/dye molecule pair [2]). Sekatskikii and co-workers [1], however, failed in demonstrating FRET transfer between a scanning NV and a dye molecule, despite previous demonstration of FRET to dye molecules covalently bonded to NDs (e.g. Ref [2]). This finding might relate to a varying quantum efficiency (QE) for NV centers in NDs [3] as well as an insufficient distance control when attaching a ND to a scanning probe tip.

Our goal is to address these two issues: We use a shallow (so far stationary) NV in a single crystal nanostructure, to minimize the NV-to-surface distance. We thus mimic the situation attainable with scanning probe devices sculpted out of single crystal diamond [4]. We characterize NVs in nanostructures and pre-select them according to their internal quantum efficiency. To bring dye molecules close to the NV centers, we will use nano-sized tips coated with dye molecules.

We present here our first steps toward FRET with NV centers in single crystal diamond. We measure the fluorescence lifetime for shallow (< 8 nm) NV centers. We map lifetime and photoluminescence vs. tip-position for a metal coated tip, see Fig. 1 a) and inset in Fig 1 b). From these measurements, we obtain the internal quantum efficiency of our NV centers [2] and verify if we can attain tip-sample distances in which FRET (Quenching) becomes efficient, see Fig. 1 b). Simultaneously, we aim to combine these measurements with magnetic sensing techniques e.g. by using a magnetic, metallic tip, to establish a uniquely versatile scanning probe technique using NV quantum sensors.

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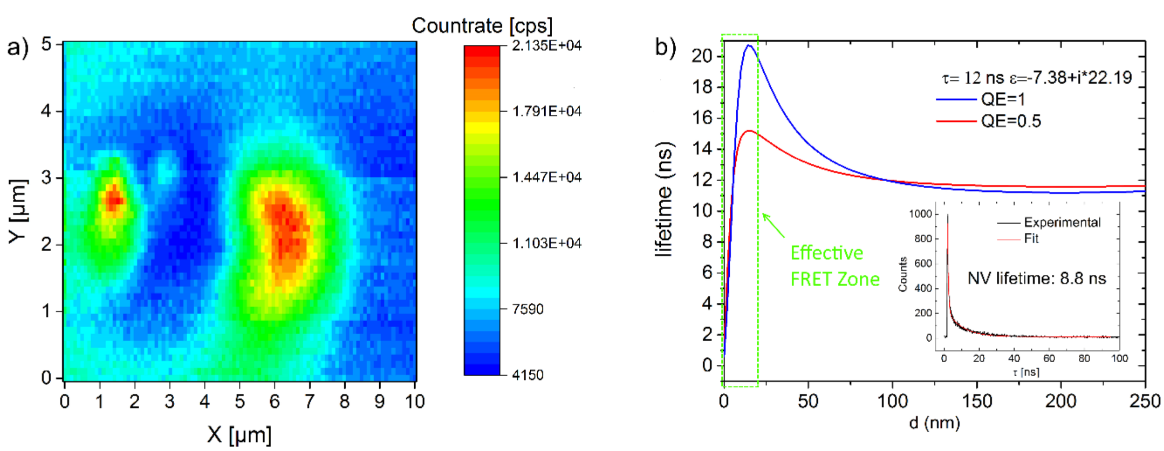

Fig. 1 a). Confocal image of a NV photo-luminescence, for different tip position. The two maxima indicate an enhanced fluorescence of the NV center as a results of the presence of the tip. b) Simulation of lifetime vs tip-sample distance for different Quantum Efficiencies. In this simulation the NV center is approximate to a dipole placed 8 nm below the surface and oriented perpendicular to the surface. The Lifetime for infinite tip-NV distance is set to 12 ns. In the inset is represented a tipical lifetime measurements

Entanglement and Nonclassicality in Atmospheric Channels

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Abstract. Driven by the goal of establishing quantum key distribution in global communication networks, the field of atmospheric quantum optics turned into a rapidly developing and growing research area over the last years. In order to implement and optimize such quantum information applications in atmospheric channels, it is crucial to gain a profound understanding of the underlying quantum properties of radiation fields in such scenarios. Particularly, quantum light in atmospheric channels suffers from fluctuating losses [1, 2]. In this contribution, we perform a rigorous analysis of different quantum effects in the presence of atmospheric fluctuating losses. This includes single-mode nonclassicality and Gaussian, non-Gaussian, and multi-partite entanglement.

Therefore, we utilize criteria based on moments of the creation and annihilation operators. In particular, we consider the so-called matrix of moments [3, 4], which provides a hierarchy of nonclassicality and entanglement conditions. We introduce input-output relations for the matrix of moments in atmospheric channels [5] which allows the characterization of the quantum effects in such channels. This includes the full analysis of the important class of two-mode Guassian states [6].

The survival of nonclassical effects in free-space channels is shown to depend on the mean photon number and on coherent displacements. Therefore, it differs essentially from constant loss scenarios. In the case of Gaussian entanglement, our results reveal a strict dependence on coherent displacements, which is typically used for encoding information. For the prominent case of two-mode squeezed states, the increase of squeezing can frustrate the transfer of Gaussian entanglement. Moreover, we propose an adaptive method to preserve Gaussian entanglement in fluctuating loss channels. We further extend our analysis to non-Gaussian and multimode entanglement tests [5]. It is demonstrated that non-Gaussian entanglement can be more robust against atmospheric losses than the Gaussian one. Additionally, we test for entanglement in a multi-mode scenario, which is an important tool to design and develop free-space quantum networks.

In conclusion, we present a fully analytical and rigorous study of entanglement and nonclassicality in atmospheric channels. We demonstrate the general capability of free-space communication schemes to preserve entanglement for quantum key distribution. Eventually, our results will help to improve quantum communication protocols in fluctuating loss channels.

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Photon antibunching in the mesoscopic intensity domain

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Anti-bunching is one of the peculiar traits of quantum systems, evidencing the very definition of "photon" as "light quantum". For this reason, anti-bunching experiments are routinely exploited to test the quality of single-photon sources. The standard technique is based on the Hanbury Brown-Twiss interferometer, in which the emitted light is divided at a 50/50 beam-splitter (BS) and two single-photon detectors are placed at the two outputs. The presence of anti-coincidences between the two outputs reveals anti-bunching.

At higher intensity regimes, the observation of anti-bunching in terms of anti-correlations between the two BS outputs is still a signature of quantumness, as it indicates that the light at the BS input is characterized by sub-Poissonian statistics.

We report on the observation of anti-bunching obtained with conditional sub-Poissonian states of light generated in the mesoscopic domain. The experimental scheme is based on the realization of a PDC process in which multimode twin beam (TWB) states containing sizeable numbers of photons are generated. One of the two parties, say the idler, is directly detected by means of a photon-number-resolving detector, whereas the signal is divided at a balanced BS, at whose outputs other two photon-number-resolving detectors are placed. According to the rule chosen in the idler arm, the conditional states at the two BS outputs can exhibit sub-Poissonian statistics and are shot-by-shot anti-correlated in the number of photons.

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Leggett-Garg inequality violation exploiting Weak Measurements

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Measurement represents one of the key features of Quantum Mechanics [1]. The impossibility of interpreting the results of a measurement on a quantum system in terms of pre-existing values has been recognised, apart in Bell's nonlocality [2, 3] and non-contextuality [4] tests, by Leggett and Garg in the behaviour of macroscopic systems when subject to subsequent measurements [5].

In this work, we present the experimental violation of a four-measurements (including the state preparation) Leggett-Garg inequality, realised by exploiting single [6] and sequential [7] weak measurements of the polarisation of heralded single photons.

We perform our test in four different experimental conditions, obtaining results in good agreement with the quantum mechanical predictions and showing, in each case, a clear violation of the classical bound (between 3.4 and 4.4 standard deviations).

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Calculation of Three-photon Down-conversion Phase-matching in Whispering Gallery Microresonators

N. Borshchchevskaia, D. Strekalov, K. Katamadze, S. Kulik, M. Fedorov

Manipulation of multiple photon states of light is of great interest nowadays. Recently a lot of attempts were made in generation of entangled three-photon states [1–3] in a process similar to well-known spontaneous parametric down-conversion. The main challenge there is very small efficiency of the process.

At the same time, microresonators may solve the problem due to their high Q-factor. We present calculations of possible phase-matching parameters in whispering gallery modes geometry: wavelengths, polarizations and resonator characteristics. We also give estimates of three-photon generation efficiency.

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Probing macroscopic quantum superpositions and the quantum nature of gravity through levitated objects

Sougato Bose

Abstract: We will discuss theoretical proposals of how quantum superpositions of distinct centre of mass states of a nano-crystal may be created and probed purely by measuring a spin embedded in the object.
The idea is to use a levitated diamond with an NV centre spin. Next we will also describe how to reach conditions whereby two such masses interacting purely through gravitational interaction can become entangled.
Witnessing such an entanglement experimentally is equivalent to establishing the quantum nature of the gravitational field. Time permitting, we will discuss how the violation of macro-realism can be verified for a levitated nano-object in a loop-hole free manner simply by coarse grained position measurements.

Towards relativistic and quantum technologies.

Dr. David Edward Bruschi
Prof. Ivette Fuentes, Dr. Carlos Saban, Dr. Mehdi Ahmadi, Jan Kohlrus

We are living in the quantum era. Quantum technologies have reached regimes where commercial applications are being developed. Quantum technologies promise to enhance the quality of life of society by providing, for example, a new generation of electronic calculators (Quantum Computing), secure communications (Quantum Cryptography) and the infrastructure for fast and secure long distance communications (Quantum Communications).
These technologies typically operate at regimes where quantum mechanics alone is sufficient to describe and explain their regimes of operation. However, cutting edge experiments have reached regimes where relativistic effects cannot be ignored.

The novel field of relativistic quantum information aims at understanding physics at the overlap of relativity, quantum information science and quantum mechanics. Quantum field theory in curved spacetime is at its core, and it allows us to understand the role of quantum systems that propagate at high speeds or on curved backgrounds within quantum information protocols. For example, we have recently proposed a scheme to exploit single photons and coherent states of light to establish entanglement between two nodes at different heights in the gravitational field. The presence of curvature, can be detected by employing quantum metrology techniques, and we were able to propose novel and more precise ways to measure relativistic parameters, such as distances.
Further development in this field will enable us to harness the potential that lies at the overlap of relativity and quantum theories, allowing us to develop the next regeneration of quantum technologies.
However, a more ambitious goal is at hand. Quantum technologies, and advances in the field of relativistic and quantum information, might ultimately allow us to propose tests of our most established theories, with the hope of providing new insight and guidance for theoretical efforts.

We have recently proposed a novel gravitational wave â€œantennaâ€, based on micrometer quantum systems known as Bose-Einstein Condensates (BECs). This proposal is of utmost importance given the recent detection events announced by LIGO. Our antenna exploits phononic excitations in the condensate and specific dynamical Casimir-like resonances that are obtained when the phononic frequencies are tailored to specific gravitational wave emissions.
We show that, potentially, our antenna can lead to sensitivities comparable with LIGO and even outperform it for specific applications.â€¨Our current work focuses on developing the preliminary provocative proposal into a full-scale technology, with foreseen applications within 10 years.
This antenna promises to open a new eye on our universe, allowing diverse applications ranging from precise positioning of sources, due to the possibility of building and deploying large amounts of micrometer BEC-based antennas, to cost-effective, affordable and versatile systems which can be easily tailored to different sources, regimes and scenarios.
Overall, given that the core theory of our antenna lies at the intersection of gravity and quantum physics, we believe that it will aid us in unveiling novel phenomena by detecting small discrepancies with accepted theories, such as quantum field theory in curved spacetime, therefore challenging our understanding and potentially contributing to deepening our understanding of the Universe.

Maximal Coherence and the Resource Theory of Purity

A. Streltsov, H. Kampermann, S. Woelk, M. Gessner, **D. Bruss**

The resource theory of quantum coherence studies the off-diagonal elements of a density matrix in a distinguished basis, whereas the resource theory of purity studies all deviations from the maximally mixed state.
We establish a direct connection between the two resource theories, by identifying purity as the maximal coherence, which is achievable by unitary operations. The states that saturate this maximum identify a universal family of maximally coherent mixed states.These states are optimal resources under maximally incoherent operations, and thus independent of the way coherence is quantified.
For all distance-based coherence quantifiers the maximal coherence can be evaluated exactly, and is shown to coincide with the corresponding distance-based purity quantifier.
We further show that puritybounds the maximal amount of entanglement and discord that can be generated by unitary operations, thus demonstrating that purity is the most elementary resource for quantum information processing.

Generation of Sub-Poissonian Light of High Photon Number

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In a simplest mean-field approach, the photon number in a laser cavity follows by equating gain and loss. It is the solution to the equation [1] (gain on the left, loss on the right)

$$pn/n_{\mathrm{sat}}(1 - n/n_{\mathrm{sat}}) = n/n_{\mathrm{sat}}\,,$$

where n is the photon number, p is a dimensionless pump parameter (scaled by the loss rate), and n_{sat} is the saturation photon number. Below threshold (p less than 1), $n/n_{\mathrm{sat}} = 0$ is the only acceptable solution; otherwise, there is also the solution with the laser turned on, i.e., $n/n_{\mathrm{sat}} = (p - 1)/p$. The “turned on” solution is stabilized by gain saturation, where $1 - n/n_{\mathrm{sat}}$ falls as n/n_{sat} grows; notable, though, since n_{sat} is large (on the order of 10^4−10^8), this mechanism is insensitive to fluctuations in n on the order of ±1. In this talk, we propose a source of light where gain stabilization by one added or subtracted photon generates enough squeezing to produce photon numbers, per output pulse, in the region of $n = 100 \pm 2$ (Mandel Q of -0.96). The proposal is based on micromaser ideas [2,3], where the existence of so-called “trapping states” [4] provides for the required strong nonlinearity of the gain function. We report results from extensive quantum trajectory simulations, where, unlike in Ref. [3], for example, the simultaneous interaction by multiple injected qubits is allowed [5], along with simultaneous photon loss. This enables access to many different operating branches, separated from one another by trapping states. We implement measure-and-feedback protocols to control noise-driven switching between these branches, and thus optimize trajectories for the production of highly sub-Poissonian light. In contrast to the original micromaser [3], which was pumped by excited Rydberg atoms, injected into a resonator in an atomic beam, we have in mind a more practical realization in superconducting circuits [6,7].

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Quantum Sensing by Stochastic Quantum Zeno

Filippo Caruso

A system under constant observation is practically freezed to the measurement subspace. If the system driving is a random classical field, the survival probability of the system in the subspace becomes a random variable described by the Stochastic Quantum Zeno Dynamics (SQZD) formalism. Here, we study the time and ensemble average of this random survival probability, and demonstrate how time correlations in the noisy environment determine whether the two averages do coincide or not. These environment time correlations can potentially generate non-Markovian dynamics of the quantum system depending on the structure and energy scale of the system Hamiltonian. We thus propose a way to detect time correlations of the environment by coupling a quantum probe system to it and observing the survival probability of the quantum probe in a measurement subspace [1]. Recently, an ergodicity breaking effect in SQZD has been experimentally observed by atom-chips [2]. Finally, we show how the sensitivity of the measurement is described by a functional version of the Fisher information [3,4], as well as sensing protocols based on Optimal Control. Therefore, we expect that these results will further contribute to the development of new schemes for quantum sensing technologies, where nanodevices may be exploited to image external structures or biological molecules via the surface field they generate.

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Adaptive dynamical decoupling sequences for computing and sensing in diamond devices.

Jorge Casanova

Nuclear spins are exceptional candidates to store and process quantum information.
In this talk I will present a method based on dynamical decoupling techniques that generates highly selective filter functions ensuring individual addressing and control of nuclear spins in realistic scenarios.
I will additionally comment on the direct applications of our protocol related with quantum computing and quantum sensing.

Fundamental explanation of the quantum computational speedup

Giuseppe Castagnoli

In previous works [1,2], we showed that an optimal quantum algorithm can always be seen as a sum over classical histories in each of which the problem solver knows in advance one of the possible halves of the information that specifies the solution she will read in the future and performs the computation steps (oracle queries) still needed to reach it. Presently, we provide a fundamental justification of this fact [3].

The usual representation of quantum algorithms, limited to Alice's problem solving action, consists of the unitary transformation of an input state into an output state that encodes the solution of the problem, followed by the final measurement required to read the solution. It is physically incomplete as it lacks the initial measurement. This is restored by representing Bob's problem setting action. An initial measurement in a maximally mixed state selects a problem setting at random, Bob unitarily transforms it into the desired setting (for simplicity we jump this transformation, so that the problem setting becomes the random outcome of the initial measurement). The usual Aliceâ€™s action follows.

There is an immediate consequence. This extended representation is to Bob and any external observer, it cannot be to Alice. It would tell her the problem setting, thus the solution of the problem, before she begins her problem solving action. To Alice, the projection of the quantum state associated with the initial measurement must be postponed at the end of the unitary part of her problem solving action. Thus, the input state to her remains one of complete ignorance of the problem setting.

We find ourselves with two relational representations of the quantum algorithm. One with respect to Bob and any external observer, the other with respect to Alice.
In either representation, there is a unitary transformation between the initial and final measurement outcomes. We assume for simplicity that the solution is a bijective function of the problem setting. As a consequence, the selection of the problem setting and the corresponding solution can be performed indifferently forward in time (as usual) by the initial measurement or backward in time by the final one. In the latter case, we should ignore the projection of the quantum state associated with the initial measurement and propagate backward in time, by the inverse of the time-forward unitary transformation, the two end states of the projection associated with the final measurement.

At this point, we argue that ascribing the selection in question to either the initial or the final measurement would introduce a preferred direction of time, what would be unjustified in the present reversible context. Evenly sharing the selection between the initial and final measurements is the only way of making the representation of the quantum process time-symmetric. We do this by reducing the initial and final measurements to partial measurements that evenly and without redundancies contribute to the selection in question in all the possible ways in quantum superposition.

In the representation to Bob and any external observer, this says that half of the information that specifies the random outcome of the initial measurement has been selected back in time by the final measurement, an unverifiable and inconsequential thing.

In that to Alice, the input state of the quantum algorithm to her, of complete ignorance of the problem setting and the solution, is projected on one of lower entropy where she knows one of the possible halves of the information that specifies them. This is why an optimal quantum algorithm turns out to be a sum over classical histories in each of which Alice knows in advance one of the possible halves of the information about the solution she will read in the future and performs the function evaluations still needed to reach it.

Although just a physical interpretation of the mathematics of quantum algorithms, the present explanation of the speedup has potentially important practical consequences. Until now there was no fundamental explanation of the speedup, no unification of the quadratic and exponential speedups, no method for computing the number of function evaluations required to solve an oracle problem in an optimal quantum way.

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Time-resolved Scattering of a Single Photon by a Single Atom

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Scattering of light by matter has been studied extensively in the past. Yet, the most fundamental process, the scattering of single photons by single atoms, is largely unexplored.
One prominent prediction of quantum optics is the deterministic absorption of a traveling photon by a single atom, provided the photon waveform matches spatially and temporally the time-reversed version of a spontaneously emitted photon [1-3].
Here, we experimentally test this prediction using a single trapped atom and heralded single photons with different temporal profiles. In a time-resolved atomic excitation measurement, we find a 56(10)% increase of the peak excitation by photons with an exponentially rising profile compared to a decaying one, in agreement with a time-reversed Weisskopf-Wigner model [2]. Thus, tailoring the envelope of single photons allows better control of atom-photon interaction in quantum networks [4].
We expand our study by observing the effect of varying the bandwidth of the single photon probe on the overal interaction probability [5].

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Unbalanced SU(1,1) interferometer: phase measurement below the shot-noise level with high tolerance to detection losses

M. Manceau, F.Ya. Khalili, G. Leuchs, and M.V. Chekhova

We perform the phase measurement in an unseeded SU(1,1) interferometer composed of two cascaded optical parametric amplifiers (OPAs) with direct detection. Theoretically, such a device can provide phase sensitivity overcoming the shot-noise limit and ideally achieving the Heisenberg limit, the only obstacle being the losses inside and outside of the interferometer. While the internal losses are difficult to overcome, the external (detection) losses can be overcome by making the interferometer unbalanced, with the parametric gain of the second OPA considerably exceeding the first one [1].

In our recent experiment, we demonstrate a phase sensitivity overcoming the shot noise limit by up to 3dB, with the number of photons in the interferometer being between 1 and 10. We show that the phase sensitivity is considerably improved by increasing the parametric gain of the second OPA. In particular, we show that with the gain of the second OPA as high as 7, the phase sensitivity of the interferometer is preserved even with the detection efficiency reduced by an order of magnitude, by means of additional loss introduced in the detection scheme.

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Phase-shift keyed binary channels in the presence of phase noise using displaced squeezed states

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We address the role of the squeezing as a resource for the discrimination between two phase-shifted displaced-squeezed states (DDSs) in the presence of phase noise. The states to be discriminated are obtained by applying the displacement operator $\hat{D}(\pm\alpha)$, $\alpha \in R$, to a squeezed vacuum state such that the applied displacement differs for a phase π between the states. Throughout our analysis, we keep the channel energy N fixed, so that, if the squeezing fraction (i.e. the number of squeezed photons in the channel) is defined as $\frac{N_{sq}}{N} \equiv \beta$, the coherent fraction is $1-\beta$. We investigate whether one can attain smaller error probabilities in the discrimination by employing DSSs (i.e. $\beta \neq 0$) rather than coherent states (i.e. $\beta = 0$ case). Therefore, β is the parameter which quantifies how much our states are squeezed.

The error probability of feasible detection schemes is evaluated and compared with the minimum value allowed by quantum mechanics, the so-called *Helstrom bound*. We firstly analyse the ideal case, where the states are not affected by the noise, and evaluate the Helstrom bound. Here the signal under investigation are pure and we find a threshold value of the squeezing fraction $\beta_{th}(N)$ such that for $\beta < \beta_{th}$ the DSSs performances are better than the coherent states ones and a minimum value is attained.

Then we consider a particular detection stage and take into account a homodyne detector as receiver. This choice is based upon the result obtained in [1] which shows that homodyne detection is robust against phase diffusion. Such noise is the most detrimental for this configuration because we encode information on phase. Since a homodyne receiver measures the quadratures of the input field, it is useful to use a phase-space analysis and, by suitably integrating the DSSs Wigner distribution, we recover the error probability to be compared with the Helstrom bound.

When the DSSs are affected by phase diffusion, the corresponding Wigner functions are computed and numerically integrated. The analysis of the error probability shows that the performances of DSSs are more degraded by noise than the coherent states performances, as one may expect. Nevertheless, an optimal β-range $[0, \beta_{th}]$ such that the DSSs error probabilities are smaller than the coherent states ones still exists. In particular, here the threshold value β_{th} depends on the amount of noise in the channel and the larger the amount of noise, the smaller β_{th}. Furthermore, we show that it is possible to find an optimal β-range for every considered amount of noise: even in presence of phase diffusion there is always a β_{th} such that for $\beta < \beta_{th}$ DSSs are more distinguishable than coherent states. Recalling that squeezing is an intrinsically quantum feature, this endurance to noise for DSSs turns out to be remarkable and proves them to be a resource for binary discrimination.

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Sufficient conditions for a memory-kernel master equation

D. Chruscinski

We derive sufficient conditions for the memory-kernel governing nonlocal master equation which guarantee a legitimate (completely positive and trace-preserving) dynamical map. It turns out that these conditions provide natural parametrizations of the dynamical map being a generalization of the Markovian semigroup.
This parametrization is defined by the pair of maps —monotonic quantum operation and completely positive map—and it is shown that such a class of maps covers almost all known examples from the Markovian semigroup, the semi-Markov evolution, up to collision models and their generalization.

Local consistency of quantum nonlocality

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Nonlocality is a defining feature of quantum mechanics. Some of the quantum mechanical correlations in a bipartite Bell experiment, for instance, cannot be reproduced by a local realist model. Quantum nonlocal correlations, however, are distinguished from other nonlocal correlations by certain mathematical constraints, which otherwise have no good explanation. Why then, wouldn't Nature permit nonlocality other than that of quantum mechanics? Here we show, within a general probabilistic framework, that the uniqueness of quantum nonlocality stems from its imperfect consistency with local realist models. In particular, we show that local hidden variables theories are completely characterized by a certain set of consistency conditions. Relaxing all but one of these local requirements leads to the set of quantum-realizable correlations, again, without assuming the Hilbert space structure. Furthermore, none of the conditions holds in super-quantum theories. We thus derive a new Bell-type inequality bounding not only quantum mechanics but any probabilistic theory. This approach also leads to a profound connection between the strength of nonlocality in any probabilistic theory and uncertainty as measured by the Tsallis entropy. In a multipartite setting, relaxed local consistency leads to monogamy of correlations. This shows that a theory in which monogamy breaks is necessarily a super-quantum theory that violates all local consistency conditions.

Measurement-induced strong Kerr nonlinearity for weak quantum states of light

Luca S. Costanzo

Strong nonlinearity at the single photon level represents a crucial enabling tool for optical quantum technologies.
We report on experimental implementation of a strong Kerr nonlinearity by measurement-induced quantum operations on weak quantum states of light.
We probe the induced nonlinearity with weak coherent states and characterize the output non-Gaussian states with quantum state tomography

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QUANTUN WORLD
RETURN TO A REALISTIC VIEW

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Abstract

Until the beginning of the twenty-century the Laplacian determinism was the main dominant current of thought in science. With the rise of Copenhagen or Orthodox Quantum Mechanics in 1927, there was a big change in this state of affairs. It was a radical change, precisely the opposite extreme, to indeterminism. With Orthodox quantum mechanics, or at least some extreme interpretations of it, Reality is a making of the Observer. This Observer consciousness has the capacity of out of a bunch of multiple potentialities or probabilities making one of them real.

As is well known, there were many thinkers, namely, de Broglie, Einstein, Schrödinger and many other that always objected to this view of the word and tried to recover causality. This task was not easy, in fact practically impossible, because they implicitly accepted the rules of the game proposed by Niels Bohr. These implicit rules, came from Fourier ontology. This way of understanding Nature, claims that only the infinite, in space and time, harmonic plane waves do have a pure single frequency. Furthermore, connects their temporal and spatial frequencies with the phenomenological fundamental formulas of quantum physics, the ones of Planck and de Broglie. In this conceptual framework, were absolute nonlocality, both in time and space, rules, individuality and causality are impossible.

To recover individuality and causality and return to a sane Realistic view of Nature it is necessary, just from the start, to reject Fourier ontology.

With the development of modern nonlinear quantum physics, following de Broglie research program, things were clarified. Now, we dispose of sound evidence coming both from theoretical and experimental domains clearly showing that a realistic view of the quantum world not only is possible but even more is necessary.

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Quantum mechanics under X Rays in the Gran Sasso underground laboratory

Catalina Oana Curceanu

LNF-INFN, Frascati (Italy)

We are experimentally investigating possible violations of the standard quantum mechanics' predictions in the Gran Sasso underground laboratory in Italy. We test with high precision the Pauli Exclusion Principle and the collapse of the wave function (collapse models).

In this talk recent results of the experimental tests of the Pauli Exclusion Principle violation will be discussed, together with the search of the spontaneous emission of X rays predicted by the collapse models.

We present our method of searching for possible small violations of the Pauli Exclusion Principle (PEP) for electrons, through the search for "anomalous" X-ray transitions in copper and lead atoms, produced by "fresh" electrons (brought by circulating current) which can have the probability to undergo Pauli-forbidden transition to the 1 s level already occupied by two electrons; we describe the VIP2 (VIolation of PEP) experiment under data taking at the Gran Sasso underground laboratories and a recent feasibility test with Germanium detectors measuring lead target.

The final aim is to test the PEP for electrons with unprecedented accuracy, down to a limit in the probability that PEP is violated at the level of 10**-31. We show preliminary experimental results and discuss implications of a possible violation.

We will then present and discuss results of a measurement of the spontaneously emitted radiation predicted in the framework of collapse models (dynamical reduction models) which set the most stringent limits on the collapse model parameter, lambda. Such models were put forward alternatively to the "standard" quantum mechanics' Schrodinger equation, followed by a "alla von Neumann" collapse of the wave-function, implementing a (nonrelativistic) dynamical reduction/collapse models by adding a non-linear stochastic term to the Schrodinger equation. The collapse might be induced by gravity, an we'll discuss the experimental limits we found by considering the Penrose-Diosi model. Baring on the importance of this conceptually new model(s), it is of utmost importance to study its experimental consequences, where the predictions are diverging from the standard equations, and to perform experiments to check it.

Device-independent tests of quantum states

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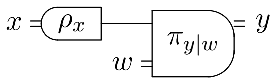
Quantum systems are most generally described by quantum states, abstract vectors in a mathematical space with the quirky property of not being perfectly distinguishable – a property called *superposition* of pure states. However, all an observer can ultimately observe are just correlations among perfectly distinguishable events in usual space and time. How can the language of the quantum realm be translated into something intelligible by an observer? Here, we construct a "Quantum Rosetta Stone", that unlocks the quantum language by providing a correspondence between quantum states and observable correlations among space-time events.

The problem is most generally framed as a game involving an experimenter, claiming to be able to prepare m quantum states $\{\rho_x\}$ and to measure them, and a skeptical theoretician who is willing to base their conclusion on observed correlations only. At each run of the experiment, first the experimenter prepares state ρ_x upon input of x, and then measures measurement $\{\pi_{y|w}\}$ upon input of w. Finally, the theoretician collects outcome y, thus reconstructing correlation $\{p_{y|x,w}\}$. The setup is as follows:

$$p_{y|x,w} := \mathrm{Tr}[\rho_x \pi_{y|w}] =$$



Let us denote with $S_n(\rho_x)$ the set of correlations generated by states $\{\rho_x\}$ for any n-outcomes measurement $\{\pi_y\}$, that is

$$S_n(\rho_x) := \left\{ p \,\middle|\, p_{y|x} = \mathrm{Tr}[\rho_x \pi_y] \right\}$$

(we take $y \in [0, n-2]$ since for $y = n-1$ one simply has $p_{n-1|x} = 1 - \sum_{y=0}^{n-2} p_{y|x}$). On the theoretician's side, the problem amounts to fully characterize $S_n(\rho_x)$, for any $\{\rho_x\}$, in order to check if $\{p_{y|x,w}\} \in S_n(\rho)$, for any w. On the experimenter's side, the problem amounts to choosing measurements $\{\pi_{y|w}\}$ generating all the extremal correlations of $S_n(\rho_x)$ (of course, the validity of the conclusion itself will be independent of $\{\pi_{y|w}\}$). Therefore, w represents a direction to be probed in the space of correlations in order to reconstruct $S_n(\rho_x)$. Since $S_n(\rho_x)$ is strictly convex, w is a continuous parameter.

In this contribution [1], we provide a full closed-form solution of this problem for the case when $\{\rho_x\}$ are qubit states – notice that this is a *restriction* on the claim to be tested, rather than an *assumption* on the actual states – and the performed measurements are tests, that is measurements with $n = 2$ outcomes. In particular, for any $\{\rho_x\}$, we explicitly derive: i) the measurements $\{\pi_{y|w}\}$ generating a correlation at the boundary of $S_2(\rho_x)$ for *any arbitrarily given direction w*; and ii) the *full closed-form characterization* of $S_2(\rho_x)$. It turns out that $S_2(\rho_x)$ is given by the convex hull of the two isolated points 0 and u (vectors with null and unit entries, respectively) and the 4-dimensional hyper-ellipsoid given by the system:

$$\begin{cases} (\mathbb{1} - Q^{-1}Q)(p - \frac{1}{2}u) = 0, \\ (p - \frac{1}{2}u)^T Q^{-1} (p - \frac{1}{2}u) \leq 1, \end{cases} \tag{1}$$

where $Q_{x_0,x_1} = \frac{1}{2}\mathrm{Tr}[\rho_{x_0}\rho_{x_1}] - \frac{1}{4}$. Furthermore, related results will be presented for the analogous problems of device-independent tests of quantum channels [2] and measurements [3].

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Anomalous Hypersignaling in Operational Theories

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One of the main tenets in modern physics is that if two space-like separated events are correlated, then such correlations must not carry any information. This assumption, constituting the so-called *no-signaling principle*, was the starting point used by Bell to quantify and compare space-like correlations of different theories on even grounds—an idea of vital importance for his argument about the EPR paradox and the derivation of his famous inequality. Subsequently, due to seminal works by Tsirelson and Popescu and Rohrlich, it became clear that the no-signaling principle alone is not enough to characterize "physical" space-like correlations: non-signaling space-like correlations allowed by quantum theory form a *strict* subset within the set of all non-signaling correlations. A natural question is then to try to identify additional principles that, together with the no-signaling principle, may be able to rule out all super-quantum non-signaling correlations at once. Various ideas have been proposed, ranging from complexity theory, e.g. the collapse of the complexity tower, to information theory, e.g. the information causality principle. However, none of these has been able to characterize the quantum/super-quantum boundary in full. In particular, an outstanding open question is whether quantum theory can be characterized in terms of the space-like correlations it allows.

In this contribution [1], we show that this cannot be done: any approach to characterize quantum theory based only on space-like correlations is necessarily incomplete unless it also takes into account time-like correlations. Our approach considers the elementary resource of noiseless communication and the input/output correlations that can be so established. By analogy with the no-signaling principle, we operationally introduce what we call the "no-hypersignaling principle," which roughly states that any input/output correlation that can be obtained by transmitting a composite system should also be obtainable by independently transmitting its constituents. As obvious as this may look, the fact that quantum theory obeys the no-hypersignaling principle is in fact a highly nontrivial consequence of a recent result by Frenkel and Weiner. We also notice that the no-hypersignaling principle is not related with temporal correlations *à la* Leggett–Garg or with phenomena such as superadditivity of quantum channel capacities.

We then construct a model theory which violates the no-hypersignaling principle but only possesses classical space-like correlations. As such, this theory would go undetected in any test involving only space-like correlations, despite displaying the anomalous effect of hypersignaling. On the technical side, our model is closely related to the standard implementation of Popescu–Rohrlich super-quantum non-signaling space-like correlations (or "PR-boxes," for short). However, while the PR-box model theory relies on entangled states to outperform quantum *space*-like correlations, our hypersignaling model relies on *entangled measurements* to outperform quantum *time*-like correlations. Nonetheless, since in our model only separable states are available, no super-quantum space-like correlation can be obtained. Therefore, while the standard PR-box model theory can be ruled out on the basis of its super-quantum space-like correlations, the model proposed here can only be ruled out by the no-hypersignaling principle.

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Permutation Modulation for Information Reconciliation in CV-QKD Applications

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Abstract

The main problem in continuous variable Quantum Key Distribution (QKD) is quantization and assignment of labels to the samples of the Gaussian variables observed at Alice and Bob. Unfortunately, most of the samples, assuming that the Gaussian variable is zero mean, tend to have small magnitudes and are easily disturbed by noise. Transmission over longer and longer distances increases the losses corresponding to a lower effective Signal to Noise Ratio (SNR) exasperating the problem. Here we propose to use Permutation Modulation (PM) as a means of quantization of Gaussian vectors at Alice and Bob over a d-dimensional space with $d \gg 1$. The goal is to achieve the necessary coding efficiency to extend the achievable range of continuous variable QKD by quantizing over larger and larger dimensions. Fractional bit rate per sample is easily achieved using PM at very reasonable computational costs. Order statistics is used extensively throughout the development from generation of the seed vector in PM to analysis of error rates associated with the signs of the Gaussian samples at Alice and Bob as a function of the magnitude of the observe samples at Bob. Finally, a coding strategy for Reverse reconciliation at Bob based on PM is presented.

Lorentz transformations from Quantum Theory of numerable systems with interactions that are local, homogeneous, and isotropic.

Giacomo Mauro D'Ariano

A recent axiomatic derivation of quantum theory and of free quantum field theory leads to a quantum walk theory of fields. The Galilean relativity principle can be semantically translated for a general dynamical system, and for the case of a quantum walk it corresponds to the invariance of the walk with the representation. The Lorentz transformations make a nonlinear group (the theory is a model for the so-called "doubly special relativity"), and the usual linear transformations are recovered in the small wavevector regime, corresponding to the whole physical domain experimented so far. The notion of particle is still that of PoincarÃ© invariant. New interesting emerging features with General-Relativity flavour will also be presented.

Partial distinguishability in fermionic interference

Hubert de Guise

We discuss the symmetries associated with partial distinguishability of fermion interferometric landscapes.

We highlight and contrast the connection with boson interferometry, and discuss the use of immanants and associated Young diagrams in the analysis of coincidence rates.

COSMOLOGICAL INFLATION , QUANTUM HIGGS FIELD AND THE COSMOLOGICAL CONSTANT PARADOX IN THE WEYL-GEOMETRICAL UNIVERSE

Francesco De Martini

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The nature of the scalar field responsible for cosmological inflation, the “inflaton” is found to be rooted in the most fundamental concepts of Weyl Differential geometry. Within this geometrical scenario and of the general-relativistic scenario of a Dirac-Weyl scalar-tensor theory, the standard electroweak theory of lep-tons based on the SU(2)*U(1) as well as on the conformal groups of Weyl’s transformation leads to an in-triguing connection with the Higgs field, the pervasive scalar field that determines the mass of all quantum particles in the Universe. While the mass of the Higgs boson M(h), measured at CERN in the year 2012, is a “free parameter” according to the standard electroweak theory, according to our theory M(h) is propor-tional to the mean value of the product of the Planck mass and of the mass corresponding to the measured amount of vacuum-energy in the Universe, i.e. 10^(-3) (eV/c^2). In virtue of an “Effective Cosmological Potential” introduced by our theory, the intriguing “Cosmological Potential Paradox, ”[The source of*] profound public humiliation for theoretical physicists”*, according to Antony Zee, has been resolved.

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5. Specify if you prefer poster/oral presentation: oral presentation
6. Title and abstract

Precision quantum thermometry achieved via local and sequential measurements.

Current technology permits the realization of extremely small thermometers, conceived in order to carry out the challenging task of controlling the thermodynamical behavior of physical systems at the spatial resolution of the micro- and nanometer length scales. In this regime the quantum correlations shared among the subcomponents of the system can play a non-trivial role in the measurement of the system temperature. We have approached this kind of questions by feeding them into the framework of quantum estimation theory.

Notably, in a recent paper [1] we have introduced a kind of mesoscopic version of the heat capacity, the so-called *local quantum thermal susceptibility*, which rigorously quantifies the highest achievable accuracy for estimating the temperature of a quantum system at thermal equilibrium when technical/practical limitations restrict our capabilities to local probing. This analysis fills a gap left uncovered by the typical mindset underpinning quantum and classical thermodynamics statements, according to which the thermal properties of physical systems are retrieved from averaging procedures which smoothen out local details. Exploiting the basic concepts of quantum estimation theory, our method provides an operative strategy to address the local thermal response of arbitrary quantum systems at equilibrium, without introducing any additional hypothesis neither on the system Hamiltonians nor on the state of the local subsystems.
The computation of the local quantum thermal susceptibility requires an exact diagonalization of the density matrix associated to the probed subsystem. This in general represents a quite non trivial point to be addressed. However in [2] we manage to show that this functional is close to the variance of its local Hamiltonian, provided the volume to surface ratio of the subsystem is much larger than the correlation length. Apart from greatly simplyfing the determination of the ultimate precision of any local estimate of the temperature, this result also rigorously determines the regime where interactions can affect the local thermometric precision.

We have finally focused on another specific, yet rather general, thermometric task: the temperature estimation of an external bath. This is typically achieved by putting in thermal contact with the bath a probing system, and by monitoring the transformations induced on it by the reservoir. In [3] we have compared the performances of sequential measurement schemes where the probe is initialized only once and measured repeatedly during its interaction with the bath, with those of measure & re-prepare approaches where instead, after each interaction-and-measurement stage, the probe is reinitialized into the same fiduciary state. From our analysis it is revealed that the sequential approach, while being in general not capable of providing the best accuracy achievable, is nonetheless more versatile with respect to the choice of the initial state of the probe, yielding on average smaller indetermination levels.

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The nature of the photon in David Bohm's interpretation of quantum field theory

Following pioneering work towards the end of the last century, the behaviour of massive particles according to de Broglie-Bohm quantum theory is by now well known. Quantum interference [1], tunnelling [2], spin [3], measurement [4], transitions [5], non-local correlations with entangled states [6] and much else [7] have each been clearly explained in terms of the individual particle motions that form the basis of de Broglie-Bohm theory.

Bohm's approach to quantised fields [8] is not so well known, but an equally deterministic and cogent picture emerges of the behaviour of well-defined quantum fields when Bohm's approach is followed. In this contribution, I use Bohm's approach to review a number of simple models of the behaviour of quantum fields and their interaction with matter (in low energy regimes) [9]. These models show that the quantised field has a well defined extended form in space and a well-defined motion (just like a classical field), but (unlike the classical case) the field's evolution is determined by a guiding wave functional. The particle-like nature of the field is only revealed in its interaction with matter, this, of course, is generally accepted[1]. In Bohm's approach "the photon" is simply a quantised field excitation and there are no photon trajectories. I show how, nonetheless, the behaviour of quantum fields in interaction with quantised matter can be accounted for with a well-defined and continuously evolving field correlated with massive particle trajectories.

A particularly instructive example is the entanglement of two, two-level atoms arising through their interaction with a single mode of an appropriately tuned quantum field [7]. Using this model it can be shown that, if at the outset the quantum field contains a single photon excitation whilst the atoms are initially in their ground states, then an entangled state develops with time. At the point in time when the "photon" excitation is removed, and the field is in the ground state, the atoms become entangled such that only one of the atoms may be found to be excited on measurement. In Bohm's approach, the atom that will actually be found to be excited on measurement is determined at the outset. The specific outcome depends on the evolution of the joint wave function and the specific initial conditions (massive particle positions and field mode amplitudes) that pertain in a given individual case. The nonlocal behaviour of the entangled atoms-field system can be clearly exhibited in the system's configuration space as the simulations I present will show.

Bohm's approach to the entangled atoms-field system is then used to describe what happens in the "Interaction-Free Effects Between Distant Atoms" scenario that has recently been discussed by Aharonov et al [10]. As always, when applying de Broglie-Bohm theory, the paradoxical behaviour disappears to be replaced, notwithstanding nonlocal effects, by an intuitive explanation of the behaviour of the system in terms of well-defined fields and definite particle trajectories. As is usual in deterministic systems well-defined initial conditions yield well-defined outcomes.

I also review some of the recent experimental evidence [11], [12] which purportedly allows the reconstruction of photon trajectories through average values of weak measurements of the local field momentum.

Finally, I mention briefly the prospects for a theory based on photon trajectories [13].

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Prefer Oral contribution

Quantum mechanical violation of macrorealism for large spin and for large mass using the harmonic oscillator coherent state

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Abstract

This talk seeks to provide an overview of the core ideas and key results of two different types of recent studies showing the quantum mechanical (QM) violation of macrorealism (MR) in the so-called classical limit:

(a) For multilevel spin systems, using two different necessary conditions of MR, namely, the Leggett-Garg inequality (LGI) and Wigner's form of the Leggett – Garg inequality (WLGI), the extent to which the QM violation of MR can be demonstrated in the *asymptotic limit of spin*, even for *arbitrary* coarse-grained or unsharp (noisy) measurements, is investigated. It is shown that classicality in the sense of satisfying MR does *not* emerge in the asymptotic limit of spin, whatever be the unsharpness or coarse-grainedness of measurements.

(b) The QM violation of LGI or WLGI in the context of a linear harmonic oscillator is invoked to reveal non-classicality of the state which is considered the most "classical-like" of all quantum states, namely the Schrodinger coherent state. In the *macrolimit*, the extent to which such *nonclassicality* persists for *large values of mass* and *classical amplitudes of oscillation* is quantitatively investigated, and the relevant results will be presented, suggesting a possible experimental setup using nano-objects.

Electrical control of NV centers in diamond with graphitic electrodes fabricated by MeV ion implantation

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Color centers in diamond are promising systems for the development of appealing quantum technologies. As several ground-breaking works in this research field were achieved by means of the optical stimulation of NV centers, an efficient electrical control of their photo-physical properties would enable a further degree in integration in opto-electronic quantum devices. The fabrication of integrated graphitic micro-channels allows to define arbitrary electrode geometries in the diamond bulk (i.e. up to several micrometers below the sample surface) by exploiting the radiation-induced graphitization of the material occurring at the end of the MeV ion penetration range [1], and could therefore represent a useful strategy to achieve such integration.

In this work, we present results obtained on devices consisting of pairs of sub-superficial (i.e. ~3 µm deep) graphitic micro-electrodes with ~10 µm spacing, fabricated into single-crystal diamond substrates with a 6 MeV C^{3+} microbeam. The current-voltage characteristics of the graphite-diamond-graphite junctions displays an ohmic behavior, associated with a moderate current injection ("low-current regime") at bias voltages below a threshold value V_c. At $V > V_c$, the device exhibits an abrupt transition to a high-current regime dominated by a Poole-Frenkel conduction mechanism and providing stimulation of electroluminescence emission from NV centers and interstitial-related defects in the inter-electrode gap [2].

The electroluminescence spectral analysis evidenced a bright emission from native neutrally-charged nitrogen-vacancy centers (NV^0). Moreover, the graphitic micro-electrodes were exploited to stimulate single-photon emission from isolated NV^0 centers in an "electronic grade" diamond sample through the injection of a stable and non-destructive pump current in the inter-electrode gap.

Ensemble photoluminescence (PL) spectra (532 nm laser excitation) acquired under electrical bias in low-current regime exhibited a linear increase with the injected current in the NV^- population at the expense of the NV^0 charge state [3]. This result indicates the effectiveness of graphite-diamond-graphite junctions to stabilize the negative charge state of the NV centers for spin manipulation protocols. Finally, the distribution of the electric field in the active region of the junction was investigated by spatially mapping the Stark-shifted optically-detected magnetic resonances (ODMR) from NV centers in the active region of the device.

These results provide promising perspectives on the utilization of integrated electrical structures for the stimulation and control of deep color centers in diamond located at micrometric distances from the diamond surface, for which longer spin coherence times are expected [4].

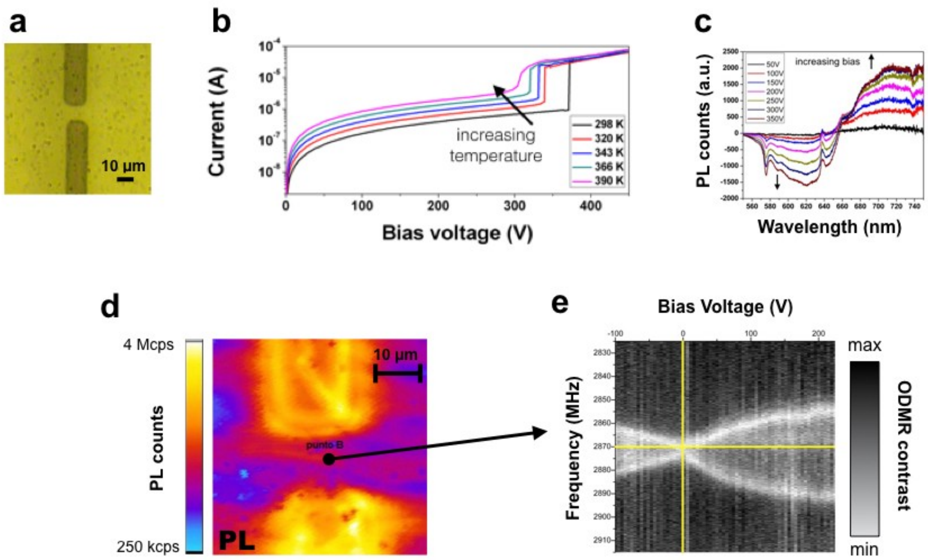

Figure: a) Optical micrograph of a graphite-diamond-graphite junction; **b)** Temperature-dependent current-voltage characteristics;
c) relative variation of PL spectra under increasing bias voltage; **d)** Photoluminescence spectrum of the graphite-diamond-
graphite junction under 532 nm laser excitation; **e)** Stark shifting of the ODMR resonances of NV centers acquired from the highlighted point at center of the junction.

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New uncertainty relations for two, three and four observables

Viktor Dodonov

It is impressive that 90 years after the birth of uncertainty relations in Quantum Mechanics [1,2], this subject is still "alive".
Moreover, one can observe some "burst" of publications in this area, devoted to generalizations of the traditional product inequalities found in [1,2] and to new forms of the uncertainty relations, such as "entropic uncertainty relations" (see [3,4] for recent reviews) or "sum uncertainty relations" [5,6].

The aim of my talk is to report on some new relations that were not found in the available literature. Even for two observables, some new inequalities were discovered recently [5,7,8]. The main result of such generalizations is the increase of the right-hand side of the standard commutator uncertainty relation [1,2], if some additional information on the statistical properties of the quantum system is known, such as the correlation coefficient betwee two observables [9] or the degree of purity of the quantum system [10]. Now I will show, how the uncertainty product is increased due to non-zero correlations of the two-varaible system under study with some extra variables, describing the "external world".

The uncertainty relations for an arbitrary set of N observables were derived for the first time by Robertson [11], and many their special cases and generalizations were given in the review [12].
Unfortunately, such inequalities are too complicated in the general case, because they contain, besides N variances of the observables, numerous combinations of N(N-1)/2 covariances and N(N-1)/2 mean values of commutators. I show a generalization of RobertsonÂ´s scheme, which allows to get rid of N(N-1)/2 covariances. The new inequalities for three and four observables are simpler and more tractable than those given in the available literature.

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Meaning of null weak values

Q.Duprey

Meaning of null weak values

First introduced by Aharonov, Albert, and Vaidman, weak measurement are a form of non-destructive measurement which allow us to extract information regarding the value of an observable as the system evolves from a given prepared state to a well defined final state obtained by making a standard measurement of another observable [1]. The measurement outcome called the weak value of an operator is a complex number whose physical meaning is still being debated. A particularly clearcut arises when the weak value vanishes and it has been generally vaguely interpreted as the observable being absent at the location where the weak measurement took place. Such interpretations have given rise to effects suc as the "Quantum Cheshire Cat" [2] or the discontinuous traces left by a particle that can take several different paths (as in an interferometer) [3].

While these apparently effects have been heavily criticized, an analysis of the meaning of null weak values is still lacking. In our work, we investigate the physical implications of vanishing weak values of a projector operator as well as a general observable. We argue that such particular weak value can be understood thanks to the standard description of transition amplitude between well known initial and final state. From this point of view, the inference about the "absence" of a property at a given location is possible in the case of successful post-selection only. An illustration of apparent discontinuous trajectories in a three path interferometer is provided (see Figure in attached file).
Moreover, we argue that inferring particle's past should involve all of its properties and not only its past trajectory whose correspond to a classical point of view. Indeed, it has been observed that weak measurements of different properties are non zero at different locations [2]. It follows that a quantum system have to be considered as an extended undulatory entity whose local properties depend on interfering paths.
Consequently, we conclude that the observation of discontinuous traces of a property is an indication that the wave function is related to a physical phenomenon, rather than being a mere computational artefact.

Caption of the figure attached to the mail
A three-path interferometer for spin-1 particles with a provisions for recombination of the two lower paths. Weak measurements take place at timeÂ t_k at the points shown. We observe an apparent discontinuous trajectory on the two lower paths where the weak value of the operator projector is zero at O and O' while it is non zero at E, E', F and F'.

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Weak Values, Eigenvalues and Expectation Values

Jan Dziewior

Weak values, which have been introduced in 1988 by Aharonov, Albert and Vaidman, to this day constitute a controversial element in the debate about the foundations of quantum mechanics [1]. They describe effective interactions of a pre- and later post-selected quantum system with external systems. These complex values can be characterized by their emergence as linear factors in the position and momentum shifts of the external system in the case of a weak interaction corresponding to real and imaginary parts of the weak value. While this property is successfully employed in several experimental techniques as for example direct state tomography [2] or weak amplification [3,4], also a rich field of discussions about the physical meaning of weak values has developed.

One particular point of interest arises from the question whether weak values represent genuinely statistical properties of physical systems in the same sense as expectation values, or whether they correspond to more fundamental properties like eigenvalues. A possible approach for resolving this question is the analysis of the pointer states after interaction with a system either described by an eigenvalue, an expectation value or a weak value. Thereby, the amount and type of pointer disturbance is used as a quantification of the statistical nature of the value describing the interaction [5]. It can be shown that in general the pointers corresponding to the eigenvalue and the weak value are fundamentally more similar than the pointers corresponding to eigenvalue and expectation value. This relation is confirmed experimentally using the polarization of light as the principal object system and the light's transversal position as the pointer system [6]. Thus, rather than having the statistical properties of expectation values, the similarity of the weak value to eigenvalues indicates that it is a definite property of pre- and post-selected quantum systems.

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The Case of the Disappearing (and Re-Appearing) Particle

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A novel prediction is derived by the Two-State-Vector-Formalism (TSVF) for a particle superposed over three boxes. Under appropriate pre- and post-selections, and with tunneling enabled between two of the boxes, it is possible to derive not only one, but three predictions for three different times within the intermediate interval. These predictions are moreover contradictory. The particle (when looked for using a projective measurement) seems to disappear from the first box where it would have been previously found with certainty, appearing instead within the third box, to which no tunneling is possible, and later re-appearing within the second. It turns out that local measurement (i.e. opening one of the boxes) fails to indicate the particle's presence, but subtler measurements performed on the two boxes together reveal the particle's nonlocal modular momentum spatially separated from its mass. Another advance of this setting is that, unlike other predictions of the TSVF that rely on weak and/or counterfactual measurements, the present one uses actual projective measurements. This outcome is then corroborated by adding weak measurements and the Aharonov-Bohm effect. The results strengthen the recently suggested time-symmetric Heisenberg ontology based on nonlocal deterministic operators. They can be also tested using the newly developed quantum router.

Quantumness of Hamiltonian cellular automata and indications for "prequantum" states

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Abstract. The quantum mechanical features of Hamiltonian cellular automata (CA) are reviewed, *i.e.* of CA described by integer valued variables and couplings that follow linear updating rules. We then discuss whether, in this class of CA, there is room for single or multi-partite systems that evolve by permutations of a set of *ontological* states, thus providing examples for G. 't Hooft's recent *CA Interpretation of Quantum Mechanics*. This is indeed the case for systems consisting of a single or multiple two-state components, interacting similarly as in the Heisenberg model of a ferromagnet. Initial conditions play a decisive role in avoiding the formation of unwanted superpositions of these prequantum states, unlike the most common situation in quantum mechanics.

Title Common sense in quantum mechanics

Berge Englert

We analyze Vaidman's three-path interferometer with weak path marking [Phys. Rev. A 87, 052104 (2013); Phys. Rev. Lett. 111, 240402 (2013)] and find that common sense yields correct statements about the particle's path through the interferometer.
This finding is at odds with the original claim of non-commonsensical discontinuous particle paths.
Here, "the particle's path" has operational meaning as acquired by a path-discriminating measurement.

Quantum coherently-driven charge transport across two SQUIPTs coupled by a Coulomb island

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The second quantum revolution is now reaching many aspects of everyday life of science and technology. Actual research on the manipulation of quantum phenomena at the level of artificial atoms and qubits mainly focuses on nanostructured superconducting circuitry.

Quantum superposition states are intrinsically sensitive to the environment, and in cQED this sensibility can be tuned on demand by intentionally varying the degree of coupling.

Several proposals have been presented in the last ten years for the realization of robust qubits suitable for quantum computing, quantum-enhanced standards, and sensing purposes. Three classes of devices have been populated by different approaches all based on the compromise between the “quantumness” of the system and its operability: charge, flux and phase qubits.

The charge qubit, the very first to have been realized, has been introduced by Nakamura et al. [1] and has now reached comparable performances in terms of coherence time and QND capabilities respect to its competitors.

We will present a device concept based on the exploitation of quantum interference in short phase-biased superconducting nanowires implementing a superconducting quantum interference proximity transistor (SQUIPT) that leads to a tunable gap in the wire density of states (DOSs). A quantum-enhanced turnstile for single electrons based on SQUIPTs has been recently demonstrated exploiting analogous phenomena [2].

We will show how the flux dependence of the proximity gap induced in the weak link of a SQUIPT can be exploited as a phase-tunable energy barrier which enables quantum charge configurations with enhanced functionalities. Coupling two SQUIPTs with a metallic or superconducting Coulomb island we will present a novel single-electron superconducting transistor (called SQUISET) in which the charging landscape is coherently driven by an external magnetic field.

Resuming, this device adds new perspectives to quantum electronics being an alternative building block in fields such as quantum metrology, coherent caloritronics, or quantum information technology.

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Enormous azimuthal entanglement of noncollinear biphotons in spherical-angle variables and in Cartesian coordinates

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As well-known, in the process of noncollinear type-I spontaneous parametric scattering emitted pairs of photons propagate along the cone with signal and idler photons located approximately at opposite ends of diameters. Because of axial symmetry, the angular azimuthal entanglement of biphotons in this geometry is enormously high, with the Schmidt entanglement parameter K reaching values up to 10^4 (PRA, **93**, 033830, 2016). In this report polarization features of such photon pairs are analyzed which is important for further applications of the described highly entangled states. The same biphoton states and their entanglement are analyzed in terms of Cartesian components of transverse photon's momenta (wave vectors). In this picture a very high entanglement is found to be related to a very strong broadening of a single-particle photon distribution in dependence on one of components of its transverse wave vector, with a very narrow coincidence distribution. The degree of entanglement can be characterized in this approach by the ratio of widths of the single-particle and coincidence distributions R, which is found to be of the same order of magnitude as the above-mentioned Schmidt parameter K in the picture of spherical angles of photon's wave vectors. Experimental schemes for measuring these distributions and the arising degree of entanglement are discussed.

Four-photon interference in integrated LiNbO3 platform.

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An important and essential element in a computational infrastructure based on photons is a quantum interferometer which allows to measure the degree of indistinguishability of photons.

Such an interferometer can be realized using the well-known effect of two-photon interference, i.e., the Hong-Ou-Mandel (HOM) interference. An increase in the number of photons can increase the sensitivity of such an interferometer and simultaneously increase the entanglement of photons.

However, the realization of quantum information processes in free space is not reliable for the streaming technology because of the complexity, required precise and stable adjustment, non-stability and significant size of such systems. In contrast to such bulk optics systems, integrated circuits are characterized by a long coherence time of the photons, low losses and high brightness, have a small size and a high stability.

In this work we consider a four-photon interference in integrated LiNbO3 platform with using as a source a type II degenerate parametric down conversion (PDC) process in a periodically-poled LiNbO3 section with waveguiding achieved by infusing Titanium.

With using different optical elements it is possible to make photons totally indistinguishable before they coming into the integrated beam splitter. The coincidence probability of observing pairs of photons into different space channels was calculated. The shape of coincidence probability depends on two-photon amplitude and characteristics of integrated beam splitter.

The coincidence probability for balanced and unbalanced beam splitters with different shape of two photon amplitude (symmetrical and non-symmetrical to the signalidler variables exchange) were calculated.

The proper conditions for observing four-photon interference were studying.

Continuous-Variable Instantaneous Quantum Computing is hard to sample

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(Dated: February 20, 2017)

Instantaneous Quantum Computing (IQP) is a sub-universal class of computation that has been defined for Discrete Variables (DV) in [1]. In the original formulation, an IQP circuit requires the following ingredients: the input states are Pauli-X eigenstates, each gate in the circuit is diagonal in the Pauli-Z basis and the output corresponds to a Pauli-X measurement. Since all the gates commute they can be performed in any order and possibly simultaneously, hence the name of IQP.

We study the translation of this class of circuits to the Continuous-Variable (CV) formalism. From an experimental point of view, CVs offer the possibility of deterministically preparing resource states, such as squeezed states or cluster states, and typical measurements, such as homodyne detection, have higher detection efficiencies as compared to e.g. photon counting. In order to map the IQP paradigm from DV to CV, we use the correspondence between the universal set of gates described e.g. in [2]. CV IQP circuits have thereby the following structure: the input states are momentum-squeezed states, gates are diagonal with respect to the position quadrature and measurements are homodyne detections in the momentum quadrature. Following the lines of [1], we analyse the computational power of the CV IQP class by exploring the properties of post-selected CV IQP circuits, and we prove that CV IQP circuits are hard to sample [3]. In order to deal with post-selection in CV we consider finite resolution homodyne detectors, which leads to a realistic scheme based on discrete probability distributions of the measurement outcomes. A further peculiar element of CV that necessitate a careful analysis is the finite squeezing of the input squeezed states. We deal with this aspect by adding to the model ancillary GKP states and by relying on a GKP encoding of quantum information, which was shown to enable fault-tolerant CV quantum computation [4]. Finally, we show that, in order to render post-selected computational classes in CVs meaningful, a logarithmic scaling of the squeezing parameter with the circuit size is necessary, translating into a polynomial scaling of the input energy.

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Quantum nonlinearities induced in oscillator

(invited talk)

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Quantum nonlinear operations for harmonic oscillator systems play a key role in the development of quantum information processing, quantum metrology, quantum communication, analog quantum simulators and computers. Since a variety of strong highly nonlinear operations are unavailable in the existing physical systems, it is a common practice to approximate them by using conditional measurement-induced methods. We present feasible schemes to induce cubic and optomechanical nonlinearities using ancillary single photons and two-level atoms. The conditional approach has several drawbacks, the most severe of which is the exponentially decreasing success rate of the strong and complex nonlinear operations. We show that by using a suitable two level system sequentially interacting with the oscillator, it is possible to resolve these issues and implement a nonlinear operation both nearly deterministically and nearly perfectly. We explicitly demonstrate the approach by constructing self-Kerr and cross-Kerr couplings, which require a feasible dispersive coupling between the two-level system and the oscillator. Moreover, we extend this scheme to simulate a challenging strong optomechanical coupling impossible with current technology.

Beyond quantum Zeno subspace effect: Effective Hamiltonian and non-unitary dynamics at finite repetition rate of measurements

Sergey Filippov

We consider a quantum system dynamics caused by successive selective and non-selective measurements of the probe coupled to the system. For the finite measurement rate Ï„^âˆ’1 and the system-probe interaction strength Î³ we derive analytical evolution equations in the stroboscopic limit Ï„â†’0 and Î³^2 Ï„ = const, which can be considered as a deviation from the Zeno subspace dynamics on a longer timescale Tâˆ¼(Î³^2 Ï„)^âˆ’1 â‰« Î³^âˆ’1. Though the repeatedly measured probe evolution is frozen in the case of projective rank-1 selective measurements, the system evolution is not frozen! In fact, the system dynamics is non-linear in this case, and we derive the effective non-Hermitian Hamiltonian for such an evolution. The deduced non-linear dynamics may find applications in quantum amplifiers. Moreover, the system dynamics is analyzed for selective stroboscopic projective measurements of an arbitrary rank, when both the system and the probe evolve non-trivially. In the case of non-selective measurements, we derive the semigroup dynamics of the system-probe aggregate and find the particular form of the dissipator. Both non-linear and decoherent effects become significant at the timescale Tâˆ¼(Î³^2 Ï„)^âˆ’1, which is illustrated by a number of physical examples (Heisenberg interaction of spin particles, partial SWAP operations in quantum optics).

The report is based on the paper:
I. A. Luchnikov and S. N. Filippov. Phys. Rev. A 95, 022113 (2017).

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Quantum fluctuations and mesoscopic entanglement in many-body systems

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Abstract

Although in many-body systems the presence of decoherence is hardly negligible and emerging classicality is expected, recent experiments claim to have detected coherent quantum phenomena in systems made of a very large number of microscopic constituents. These results point to collective observables that retain a quantum character even in the thermodynamic limit; named *quantum fluctuations*, they provide the tool for studying many-body systems at the mesoscopic level, in between the quantum microscopic scale and the classical macroscopic one. We shall present the theory of quantum fluctuations adopting a general open system setting, thus taking into account the unavoidable effects of dissipation and noise induced by the external environment. Remarkably, decoherence is not always the only dominating effect at the mesoscopic scale: certain type of environments can provide means of entangling quantum fluctuations through a purely noisy mechanism.

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Microscopic origins of collective dissipation in extended systems

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Practical implementations of quantum technology are limited by unavoidable effects of decoherence and dissipation. With achieved experimental control for individual atoms and photons, more complex platforms composed by several units can be assembled enabling distinctive forms of dissipation and decoherence, in independent (separate) heat baths (SB) or collectively into a common bath (CB), with dramatic consequences for the preservation of quantum coherence. The cross-over between these two regimes has been widely attributed in the literature to the system units being farther apart than the bath's correlation length.

Starting from a microscopic model of a structured environment (a crystal) sensed by two bosonic probes [1], here we show the failure of such conceptual relation, and identify the exact physical mechanism underlying this cross-over, showing that it is not only a matter of system size. Peculiar scenarios in 1D environments or beyond isotropic dispersion relations are predicted, with collective dissipation possible for very large distances between probes, opening new avenues to deal with dissipation in phononic baths.

Further, we investigate the scenario of anomalous heating in ion traps [2], a major promising platform for quantum information processing, where this limiting factor in the rush for miniaturization is believed to be caused by a yet unknown source of dipole fluctuations in the electrodes' surfaces. A geometric crossover between CB and SB, and back to anti-CB (a common bath which dissipate the relative motion instead of the center of mass) is predicted which strongly depends on spatial correlations between dipoles, and also on their orientation. We propose a protocol to measure this peculiar effect in recent state of the art segmented Paul traps, allowing for a better insight into the microscopic origin of this elusive phenomenon.

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Quantum properties of backward parametric down-conversion

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Backward parametric down-conversion, in which one of the twin beams is generated in the opposite direction with respect to the pump laser source (Fig.1a), was theoretically predicted fifty years ago, but only recently became experimentally accessible [1], due the challenges involved in the fabrication of the required submicrometer poling period.
A peculiarity of this geometry is the presence of distributed feedback, responsible for the appearance of a threshold pump intensity, beyond which the system has a transition to coherent oscillations, i.e. it behaves as a *Mirrorless Optical Parametric Oscillator* (MOPO) [1].
This talk focuses on the quantum properties of the counter-propagating twin beams/twin photons generated below the MOPO threshold. The first part describes the coherence and correlation of the twin beams in the threshold region, where stimulated pair production is the dominant mechanism. In this regime the feedback plays a fundamental role, and we predict [2] a progressive shrinking of the emission spectra and a critical slowing down of the temporal coherence and correlation as threshold is approached.

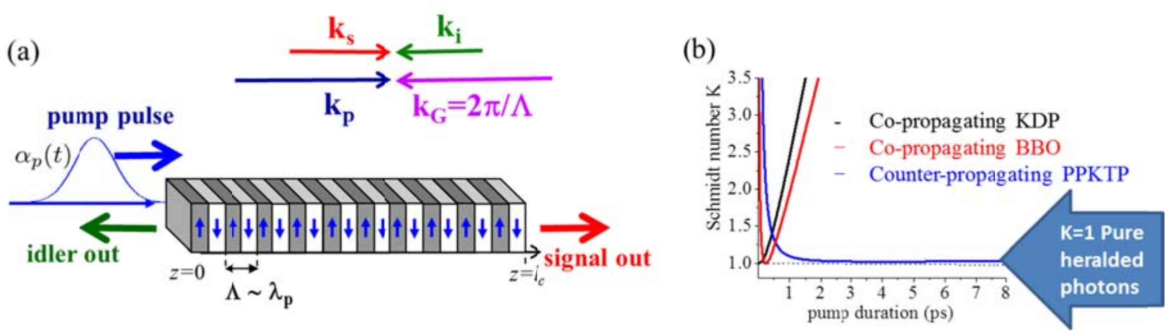

Fig1. (a) Schematics of the backward parametric down-conversion process. (b) Schmidt number characterizing the degree of entanglement of the state in the spontaneous regime. Comparison between the counter-propagating and co-propagating geometries.

The second part concentrates on the regime of spontaneous pair production, and describes the effects of the spectral properties of the pump on the degree of entanglement of the quantum state of twin photons. We show [3] that under very general and accessible conditions the state becomes almost separable, with the possibility of generating high purity heralded single-photons, characterized by a narrow frequency bandwidth (the backward propagating photon may be even more monochromatic than the pump), for a wide range of pump durations and phase matching conditions.
We offer a physical interpretation of such a behavior, and a comparison with the more conventional co-propagating geometry, where separability can be achieved only at very special matching points, by using ultrashort pump pulses[4].

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Cramér-Rao bound for time-continuous measurements in linear Gaussian quantum systems

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We describe a compact and reliable method to calculate the Fisher information for the estimation of a dynamical parameter in a continuously measured linear Gaussian quantum system.

The restriction to Gaussian dynamics, that is observed for Hamiltonians at most quadratic in the canonical operators, a linear coupling with the environment and time-continuous monitoring via Gaussian measurements [1], allows one to greatly simplify the analysis of infinite-dimensional quantum systems, and at the same time describe several state-of-the-art experimental setups in the area of quantum optics, opto-mechanics, trapped ions and atomic ensembles.

In fact, unlike previous methods in the literature, which involve the numerical integration of a stochastic master equation for the corresponding density operator in a Hilbert space of infinite dimension, the method here derived depend only on the evolution of first and second moments of the quantum states, and thus can be easily evaluated without the need of any approximation.

We also present some basic but physically meaningful examples where this result is exploited, calculating analytical and numerical bounds on the estimation of the squeezing parameter for a quantum parametric amplifier, and of a constant force acting on a mechanical oscillator in a standard optomechanical scenario.

Our results will find applications in assessing the performances of quantum sensors in several physical systems. It is worth mentioning the estimation of a magnetic field, in cases where an atomic spin ensemble can be approximated by a bosonic field, and in several other quantum optomechanics setups and estimation problems, in particular with the aim of testing fundamental theories as corrections to Newtonian gravity or to the Schroedinger equation.

Submission for oral presentation

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Coherence in Quantum Estimation

Dr. Paolo Giorda, Dr. Michele Allegra

The geometry of quantum states provides a unifying framework for estimation processes based on quantum probes, and it allows to derive the ultimate bounds of the achievable precision. We show a relation between the statistical distance between infinitesimally close quantum states and the second order variation of the coherence of the optimal measurement basis with respect to the state of the probe. In Quantum Phase Estimation protocols, this leads to identify coherence as the relevant resource that one has to engineer and control to optimize the estimation precision. Furthermore, the main object of the theory i.e., the Symmetric Logarithmic Derivative, in many cases allows to identify a proper factorization of the whole Hilbert space in two subsystems. The factorization allows: to discuss the role of coherence vs correlations in estimation protocols; to show how certain estimation processes can be completely or effectively described within a single-qubit subsystem; and to derive lower bounds for the scaling of the estimation precision with the number of probes used. We illustrate how the framework works for both noiseless and noisy estimation procedures, in particular those based on multi-qubit GHZ-states. Finally we succinctly analyze estimation protocols based on zero-temperature critical behavior. We identify the coherence that is at the heart of their efficiency, and we show how it exhibits the non-analyticities and scaling behavior proper of a large class of quantum phase transitions.

Time evolution of closed or open quantum systems with logarithmic-like spectra

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According to the basic principles of quantum mechanics, the long time decay of the survival amplitude of a unstable quantum state is not exponential [1]. The inverse power law decays of the survival amplitude and the inverse power law relaxations of the instantaneous energy to the minimum energy of the spectrum have been extensively studied [2] and have been detected experimentaly in a variety of quantum systems [3]. On the theoretical side, the introduction of removable logarithmic singularities in the energy distribution density leads to model-independent decays that depart over long times from inverse power laws. In fact, by considering, in addition to power laws, arbitrary powers of logarithmic forms in the low-energy spectrum, we find, over long times, model-independent decays of the survival amplitude that are slower than exponential relaxations and are arbitrarily faster or slower than inverse power laws [4]. Same behavior is found by studying the long-time relaxations of the instantaneous energy to the minimum energy of the spectrum. For various open quantum systems the time evolution can be described in terms of the spectral density of the system [5,6]. The introduction of logarithmic singularities in the low frequency structure of the spectral density provides in the bath correlation function [7] and in the non-equilibrium energy of the environmen [8] the variety of logarithmic relaxation described above [9]. In local quantum dephasing channels, non-Markovian evolution, recoherence and back-flow of quantum information appear for ohmic-like spectral densities uniquely above a temperature-dependent critical value of the ohmicity parameter [6]. Over long times, regular patterns are found in the direction of the information flow. In fact, back-flow of information appears in correspondence of periodical intervals of the ohmicity parameter, for both structured reservoirs of frequency modes and for thermal baths [9]. The regular patterns are not altered if the low-frequency ohmic-like profiles of the spectral densities are perturbed with additional factors that consist in arbitrary powers of logarithmic forms. Consequently, the long-time flow of information can be controlled, directed and reverted by engineering a wide variety of reservoirs that includes and continuously departs from the ohmic-like structure at low frequencies. Non-Markovianity and recoherence manifest under the same conditions along with the back-flow of information.

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Laser threshold magnetometry: new approaches to sensing with diamond

Andrew Greentree

The nitrogen-vacancy colour centre in diamond has shown great promise as a bio-sensor with the ability to sense weak magnetic fields within the body, and indeed within individual cells.
This sensing ability derives from a number of factors, principally room-temperature optically-detected magnetic resonance (ODMR), which enables readout of the spin states of individual nitrogen-vacancy centres.
Moving from single-centre to ensemble approaches introduces challenges, one of the greatest being the optimal collection of fluorescence signal.
Here we consider a qualitatively different approach to magnetic field sensing from all those used previously.
We envisage using an ensemble of nitrogen-vacancy centres as a laser medium in their own right.By combining laser operation with ODMR, we show that the coherent laser output from the nitrogen-vacancy laser is responsive to external magnetic fields.
Our calculations show that such a laser with millimeter size sensing volumes would be capable of fT/√Hz sensitivity, which is suitable for applications in magneto-encephalography, magneto-cardiology, and mining exploration.

Spacetime dimension at the Planck scale

Giulia Gubitosi

I will introduce a few different notions of spacetime dimensionality that are meaningful in the quantum gravity regime: the thermal dimension, the spectral dimension and the vacuum fluctuations dimension. I will discuss how each of these is related to properties of physical systems and will show that running spacetime dimension affects measurable properties of the early universe.

A. H. Hamici-Bendimerad.

Using the deformed exponential of the generalized formalism of non-extensive statistical dynamics, we generalize two asymmetric quantum cloning machines which produce two nonidentical copies. The non-extensive effects on the explicit cloning transformations are studied in d dimensions. This generalization includes optimal asymmetric economical and non-economical 1â†’2 phase-covariant cloners. By studying and comparing the fidelity distributions of these machines, we show that the non-extensivity affects the ancillary system. Unlike the standard treatment, by using a strongly non-extensive transformation, the cloner which works without ancillary system outperforms the non-economical one. We also have remarked that for all dimensions, non-extensive effects vanish completely in the symmetric procedure. In comparison with the standard treatment, we also investigate the distribution of quantum Fisher information (QFI) in the optimal asymmetric non-economical machine. We find that, for a weakly non-extensive transformation and for d â‰¤ 18 , this distribution is the same as in the standard case. Also, one can remark that the effects of non-extensivity in QFI are completely relaxed, essentially when d â‰¤ 18 , whereas for d>18 they appear progressively. In the latter case, by comparing QFI of the standard and non-extensive treatments, we find that some but not all asymmetric non-extensive machines may be better than the usual asymmetric cloner.

Fidelity of a d-dimensional optimal non-extensive asymmetric phase-covariant cloner

R. Boudjema, A-H. Hamici-Bendimerad, M. Hachemane, A. Smida

Abstract

Using the deformed exponential of the generalized formalism of non-extensive statistical dynamics, we generalize two asymmetric quantum cloning machines which produce two nonidentical copies. The non-extensive effects on the explicit cloning transformations are studied in *d* dimensions. This generalization includes optimal asymmetric economical and non-economical $1 \rightarrow 2$ phase-covariant cloners. By studying and comparing the fidelity distributions of these machines, we show that the non-extensivity affects the ancillary system. Unlike the standard treatment, by using a strongly non-extensive transformation, the cloner which works without ancillary system outperforms the non-economical one. We also have remarked that for all dimensions, non-extensive effects vanish completely in the symmetric procedure. In comparison with the standard treatment, we also investigate the distribution of quantum Fisher information (QFI) in the optimal asymmetric non-economical machine. We find that, for a weakly non-extensive transformation and for $d \leq 18$, this distribution is the same as in the standard case. Also, one can remark that the effects of non-extensivity in QFI are completely relaxed, essentially when $d \leq 18$, whereas for $d>18$ they appear progressively. In the latter case, by comparing QFI of the standard and non-extensive treatments, we find that some but not all asymmetric non-extensive machines may be better than the usual asymmetric cloner.

Mode analysis of higher-order transverse-mode correlation beams in a turbulent atmosphere

Authors: H. Havetisyan and C. H. Monken (presenter and corresponding author)

Quantum communication, meaning the transfer of quantum states between detection/processing stations, is one of the pillars of the quantum information area. This transfer of quantum states may connect stations that are very close, as for example the logical gates inside a quantum processor, or very far apart as it may happen in quantum key distribution procedures. The reliability or even the feasibility of long distance quantum communications depends on the resilience of quantum states to deleterious effects in the communication channels.

Photons are the most convenient quantum information carriers, since they are easily generated, they can be entangled in a number of degrees of freedom, they are fairly insensitive to external noise sources, and they can be detected at reasonable rates and efficiency. Nevertheless, when propagation in open space is needed, as in ground-satellite links, entangled photon states can be degraded by the atmosphere. The main degradation factor is the atmospheric turbulence due to the refractive index fluctuations caused by the mixture of hot and cold air streams.

In this talk, we discuss the transmission of entangled two-photon Laguerre-Gaussian modes through the turbulent atmosphere and how the correlation of orbital angular momentum of photons survives the effects of turbulence.

Optimal quantum state identification with qudit-encoded unknown states

Ulrike Herzog
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We consider the problem of identifying the state of a d-dimensional quantum system, the probe qudit, which is prepared with given prior probability in a pure state belonging to a finite set of possible states. It is supposed that some or all of the states are unknown to us, but that for each unknown state we are given a reference copy of the qudit into which this state is encoded. Identifying an unknown probe state means to find the particular reference copy whose state matches the state of the probe. For this purpose a measurement for quantum state discrimination [1] has to be performed on the combined system, composed of the probe qudit and the different reference qudits. For discriminating nonorthogonal states, optimal strategies have been developed which are optimized with respect to various figures of merits.

Supposing that the possible states of the probe qudit span a D-dimensional subspace of the d-dimensional Hilbert space the qudit is defined in, we show that from the measurement for optimal state identification with d = D one can readily determine the optimal figure of merit for the case where d > D, without solving a new optimization problem. Using our method, we study the minimum-error identification and the optimal unambiguous identification of two qudit states, where either one or both of the states are unknown, and we also investigate the optimal unambiguous identification of N equiprobable linearly independent unknown pure qudit states with d > N [2]. In all cases the optimal figure of merit, averaged over the unknown states, increases with growing dimensionality d of the qudits. The results may be of interest when high-dimensional quantum states are applied, which are a resource for various tasks in quantum information and communication and which can be for instance produced as superpositions of orbital angular momentum states of a single photon.

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Temporal Vibration Operator in a Field with Time as a Dynamical Variable

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Abstract

We show that the basic properties of a non-interacting spin-zero quantum field (e.g. Klein-Gordon equation, Schrödinger's equation, probability density, second quantization etc.) can emerge from a system with vibrations in space and time. The temporal vibrations are physical quantities introduced to restore the symmetry between time and space in a quantum field. The wave function in quantum mechanics can be shown as a mathematical tool that describes the quantization of an underlying system with vibrations in space and time. The emerged quantum field can have physical vibrations despite the overall phase for the wave function is unobservable. In addition, we investigate the properties of a self-adjoint operator for the temporal vibrations. The spectrum of this operator is unbounded. It is not restricted by Pauli's suggestion that time cannot be treated as an operator base on the fact that the Hamiltonian of the system is bounded from below.

Non-Markovianity of Gaussian quantum channels

Fabrizio Illuminati

We discuss some recent results concerning the non-Markovianity of Gaussian quantum channels. In particular, we report on a simple necessary and sufficient criterion of non-Markovianity based on the divisibility property of the intermediate dynamical map, and we identify the corresponding measures for itsquantification [1].

Through these exact methods we study both the finite and the asymptotic time regimes. For a large class of Gaussian quantum channels, we show that the approximations usually considered in describing the system evolution fail to detect non-Markovianity in a broad range of physical parameters.

Finally, we compare this approach with the one based on the distinguishability between input states evolving in the channel, showing that the latter cannot properly characterize the non-Markovianity of the asymptotic dynamics [2].

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Frequency-qubit manipulation of photons

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When photons are used in quantum information processing, they are used as polarization qubits, time-bin qubits, phase qubits, or dual-line qubits. There is, however, another degree of freedom: frequency, which is not only important as remaining degree of freedom but also important as the resource for frequency multiplexing. The basics of manipulating qubits are single-qubit interference and two-qubit interference. We have developed low-loss beamsplitters in frequency domain, that is, frequency converters for single photons that maintain the coherence between the converted and unconverted parts of a photon. Using these, we performed Mach-Zehnder interferometry and Hong-Ou-Mandel interferometry in frequency domain [1][2]. All of the photon beams are degenerated in terms of spatial mode but their frequency is split/mixed. In frequency-domain HOM interferometry, for example, two photons having different colors are input at the same time into the 50/50 frequency converter, then, two photons are output in the same color, which is stochastically chosen from the original two colors. We achieved the visibility of 0.99 for MZ interferometer [1] and 0.71 for HOM interferometer [2].

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Generation of quantum correlations in two-mode Gaussian open systems

Aurelian Isar

In the framework of the theory of open systems based on completely positive quantum dynamical semigroups, we make a comparison of the behaviour of continuous variable quantum correlations (quantum entanglement, entropic quantum discord, geometric quantum discord, quantum steering) for a system consisting of:

1) two non-coupled;
2) two coupled bosonic modes embedded in a common environment of the form of a thermal bath or of a squeezed thermal bath.

We solve the Gorini-Kossakowski-Lindblad-Sudarshan Markovian master equation for the time evolution of the considered system and describe the quantum entanglement, discord and steering in terms of the covariance matrix for Gaussian input states.
Depending on the values of the parameters characterizing the initial state of the system (squeezing parameter, average photon numbers), the coefficients describing the interaction of the system with the reservoir (temperature, dissipation constant), and on the intensity of the interaction between the two modes, one may notice such phenomena like generation of quantum correlations, their suppression (sudden death), periodic revivals and suppressions, or an asymptotic decay in time of quantum correlations [1,2].

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Parameter estimation in the presence of general Gaussian dissipative reservoir

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We analyze in detail the problems of phase and frequency estimation employing a single-mode bosonic probe evolving in the presence of the most general Gaussian dissipative channel, which in principle can be non-Markovian and non-covariant. This general channel involves important physical channels such as lossy or additive noise channels as well as more exotic ones, which involve the evolution of the probe in the presence of a squeezed reservoir. A general Gaussian evolution can be modeled as coupling the system to a reservoir containing N_{th} thermal bosons and N_{sq} squeezed ones with some time-dependent coupling strength $\Gamma(t)$. It is known that for an ideal lossy evolution i.e. $N_{\mathrm{sq}} = N_{\mathrm{th}} = 0$, the precision of phase estimation $\Delta\varphi$ is, through quantum Cramer-Rao inequality, lower bounded by an SQL-like expression which is saturated in the limit of large number of probes by squeezed vacuum states [1]. Including additional source of noise from the thermal excitations of the environment reduces the precision [2] whereas environmental squeezing intuitively should help in estimation.

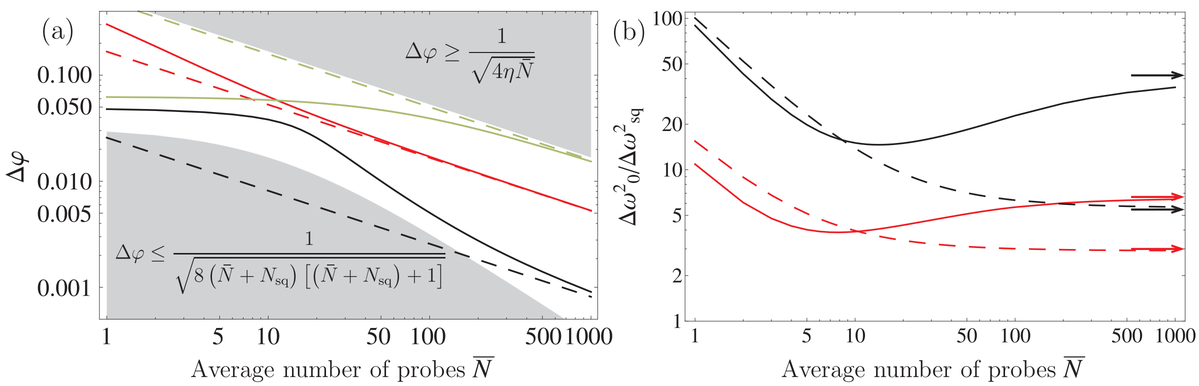

Fig. 1. (a) Exact precision bound for phase estimation in the presence of a purely squeezed dissipative reservoir with $N_{\mathrm{sq}} = 10, N_{\mathrm{th}} = 0, \eta = 0.9$ for the optimal states (black solid), coherent states (green solid) and for the standard lossy phase estimation ($N_{\mathrm{sq}} = 0$) with optimal states (red solid). Dashed lines of respective colors are the corresponding asymptotic precision bounds. The gray areas represent precision lying below the Heisenberg-limited decoherence-free bound (lower) and above the SQL bound of the standard lossy phase estimation with coherent states (upper). (b) The ratio of the exact precision bound $\Delta\omega_0^2$ for the frequency estimation in the case of standard dissipation ($N_{\mathrm{sq}} = N_{\mathrm{th}} = 0$) to the exact precision bound $\Delta\omega_{\mathrm{sq}}^2$ in the presence of a squeezed reservoir ($N_{\mathrm{sq}} = 10, N_{\mathrm{th}} = 0$) for optimal states for Markovian (black solid) and non-Markovian (red solid) evolution. Results for coherent states and asymptotic (large $\bar{N}$) values of the ratio are represented by respective dashed curves and arrows.

In [3] we show that in the limit of large number of probes the precision of phase estimation in the presence of the most general Gaussian dissipative environment is attained for squeezed vacuum states and is lower bounded by an SQL-like expression. Squeezing present in the environment can indeed enhance the precision not only when compared to the one obtainable for thermal environment with the same number of excitations but also to the precision which can be attained for ideal lossy channel of the same coupling strength, see Fig. 1(a). Similar conclusions can be drawn for frequency estimation in which one is able to optimize not only over input states but also over the time t of each subsequent measurement run, keeping the total time T of the experiment fixed. We analyzed behavior of precision in the regime of small times in which we assumed coupling strength $\Gamma(t) = \Gamma t^{\beta}$. In this model Markovian evolution is obtained for $\beta = 0$ and $\beta > 0$ represent the non-Markovian case. It can be easy to see from Fig. 1(b) that squeezing in the environment helps both in the Markovian and non-Markovian case both for optimal Gaussian states and coherent states. In the non-Markovian case the influence of a squeezed reservoir is weaker when compared to the Markovian one, although we should keep in mind that the asymptotic precision $\Delta\omega^2 T$ in the former case is better than in the latter. In all cases, however, squeezing in the reservoir is beneficial also in the asymptotic regime of large $\bar{N}$.

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Quantum sensing with diamond qubits

Fedor Jelezko

Novel sensing techniques are at the heart of a wide variety of modern technologies. Nanomedicine, molecular biology, chemistry and material science require the ability to measure properties of matter at the atomic scale.

Here we show that diamond spin sensors can provide new tool for sensing at nanoscale.

We also show how quantum error correction protocols allows to improve performance of diamond spin magnetometers.

Quantum walks and percolation

Igor Jex

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Coherent transport of excitations along chains of coupled quantum systems represents an interesting problem with a number of applications ranging from quantum optics to solar cell technology. One convenient tool for studying such processes are quantum walks. Under realistic situations quantum walks, as any genuine quantum evolution, suffers from imperfections. The influences of imperfections on quantum walks can be model in a number of ways. Recently percolation – the random formation or breaking of links between nodes – was studied is quite detail [1-4]. We present two problems involving percolated walks. First we present an implementation of quantum walks differing from the previous experiments by achieving dynamical control of the underlying graph structure and hence representing the simplest walk dynamics on a percolated graph. We demonstrate the evolution of an optical time-multiplexed quantum walk over six double steps, revealing the intricate interplay between the internal and external degrees of freedom. Second we report on the influence of percolation on the efficiency of transport, modelled by a quantum walk, on a ring. We show how the efficiency of a lazy walk can be restored when dynamical percolation is allowed.

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Focused particle beam writing for generation of structured distribution of NV color centers in single crystalline CVD diamond

Wataru Kada

Formation of atomic-scale fluorescent defects with desired structure will play an important role for development of quantum devices. Compared to the conventional strategy, creation of fluorescent defects by ion impact have higher capability for precise control of the position where color-center is created inside of desired host candidate [1]. On the other hand, there are several studies on micro-processing using various focused particle beam writing techniques to fabricate graphite structures in chemical vapor deposition (CVD) diamond to process of two- or three-dimensional microstructures [2,3]. In addition, we succeeded to control the depth of the interaction layer by changing energy of the focused ions [4]. These techniques would be applicable to form micrometer-scale fluorescence layers with desired structure by precise control of fluence and the irradiate position of focused microbeam.

In this study, we employed a focused particle beam writing technique to fabricate two-dimensional distributions of color centers. Focused proton beam with typical diameter of approximately 1 μm was irradiated to chemical vapor deposition (CVD) diamond at desired depth correspond to the penetration of projectile in diamond. NV centers are generated in relatively large area of 800 μm × 800 μm with a position accuracy with variation of the focused beam size. By employing type IIa single crystalline diamond with low concentration nitrogen impurities, distribution of NV centers with the structure of desired patterns were successfully visualized under the observation of house-made confocal microscope. Laser probe with a center wavelength of 532 nm excited NV layers and photons emitted from the centers were detected by avalanche photodiode. Concealment two dimensional matrix code into diamond by creation of the matrix of NV centers were successfully demonstrated with accuracy of 1 μm with optically detective field of the size of sub millimeters with beneath of the large scanning area of proton microbeam.

Acknowledgement:

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6. Specify if you prefer poster/oral presentation:

poster presentation

Time independent quantum circuits with local interactions

Vahid Karimipour

I introduce a scheme which uses Heisenberg spin chains with local interactions to implement quantum circuits in a time independent way without any external control. This scheme makes quantum circuits in complete analogy with classical circuits where different modules can be put together and large quantum circuits can be assembled from smaller modules.Â Our scheme is an improvement of a recent scheme, byÂ Thompson,Â Gokler ,Â Lloyd, andÂ Â Shor, Â where we have achieved to borrow an idea from quantum electrodynamics to replace non-local interactions between spin chains with local interactions mediated by an ancillary chain.

Multi-photon subtraction with use of a single APD-based detector applied to thermal states of light

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Photon addition and subtraction technique is of great interest in quantum optics, because it provides a tool for direct tests of basic commutation relations [1] and enables Schrodinger cat [2] and other non-Gaussian quantum state preparation. Also, it can be used for probabilistic linear zero-noise amplification [3].

We present a multi-photon subtraction technique using a low refractive beam splitter, followed by a non-photon number resolving avalanche photodiode detector in the reflection channel. Multiple photocounts within the correlation time of the initial state of light correspond to multiple photon subtractions. This technique was applied to the pseudo-thermal states of light, generated by laser radiation scattered on a rotating ground glass disk [4]. Up to ten-photon-subtracted thermal states have been prepared with the fidelity higher than 0.99.

Such multi-photon subtracted thermal states have increased sensitivity to any losses, which can be utilized in thermal field interferometry [5] and other metrological applications.

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Testing the foundations of quantum mechanics with multi-path interferometers

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Quantum mechanics in its modern formulation relies on several fundamental axioms. One of these axioms is that states of a system are represented by complex wavefunctions. Another, Born's rule, relates these wavefunction to measurable probabilities by stating that the probability density equates the squared magnitude of the wavefunction [1].

As it is the very nature of axioms in physics, they cannot be theoretically proven, but only tested against experiments. Interestingly, it turns out that both axioms can be tested against potential generalisations by one and the same experiment in a multi-path interferometer [2]: Complexity of the wavefunction implies that the relative phases of all path-combinations add up to zero, whereas Born's rule dictates the absence of higher order interference. Both phenomena can be tested by measuring the output signal of an interferometer with individually blockable paths and comparing the arising interferences with each other.

In this talk, I will give an introduction into the topic and present our latest results, improving previous experiments by two orders of magnitude in accuracy and precision [3]. To this end, we implemented a five-path Mach-Zehnder interferometer in free space with improved power and phase stabilisation and increased photon flux. In combination with a thorough characterisation of detector nonlinearities, this enabled us to bound the magnitude of higher order interferences relative to the usual (first-order) interference to lower than 10^{-4}, which also bounds the parameters of generalised interference models [4].

Making statements about the complexity of the wavefunction is more subtle, however, as the applied Peres-criterion [2], which tests this complexity, is biased by a variety of effects, particularly a limited coherence in the interferometer. Therefore, we have started working towards integrated waveguide interferometers, which promise reduced footprint and superior stability. First attempts in this direction have been made and show promising results [5].

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Title: "On applications of quantum information and probability outside of physics"

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oral presentation (invited)

Coautor: Irina Basieva, Department of Psychology, City University of London, UK

Recently the mathematical formalism of quantum information and probability theories started to be widely applied outside of quantum physics, from molecular biology to cognition, decision making, psychology, and economics, see, e.g., [1-5]. These applications are based on the quantum-like paradigm (Khrennikov 1999):

"The mathematical formalism of quantum information and probability theories can be used to modelbehavior not only of genuine quantum physical systems, but all context-sensitive systems, e.g., humans."

Thus **context-sensitivity** is the crucial feature leading to violation of the laws of classical probability a information. Roughly speaking, this is the common feature of electron and human (or E-coli bacteria).

The talk will give the complete (although fuzzy) image of studies in quantum-like modeling, especially in decision making. We shall also point to the links to widely discussed problem of irrationality of decision making.

We recall that as early as the 70s, Tversky (one of the most cited psychologists of all time) and Kahneman (Nobel prize in economics in 2002, for prospect theory, which he co-developed with Tversky) have been demonstrating cases where classical probabilistic prescription and human behavior persistently diverge. Today, we are at theoretical cross-roads, with huge divisions across conflicting, entrenched theoretical positions. Should we continue relying on classical probability theory as the basis for descriptive and normative predictions in decision making (and perhaps ascribe inconsistencies to methodological idiosyncrasies)? Should we abandon probability theory completely and instead pursue explanations based on heuristics, as Tversky and Kahneman proposed? However, we have to agree that the use of the probabilistic and statistical methods is really the cornerstone of the modern scientific methodology. Thus, although the heuristic approach to decision making cannot be discarded completely, it seems more natural to search novel probabilistic models for decision making. And the appeal to the quantum probability model has really revolutionized theory of decision making.

It has to be underlined that this direction of research has nothing to do with attempts to model cognition by considering the brain as a quantum physical system (e.g., in the style speculations of R. Penrose or S. Hameroff). Thus we discuss not genuine quantum physical processes in the brain behind cognition and decision making. Our approach can be applicable not only to individual bio-systems, but their societies. Thus it has applications to evolution theory, population dynamics, and social science. Recently one of the authors of this talk [5] proposed the model of *information laser* which provides the quantum-like basis for modern social technologies, from color revolutions to such recent unexpected events as Brexit and the election of Donald Trump as the president of USA.

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On applications of quantum information and probability outside of physics

Andrei Khrennikov

Coautor: Irina Basieva, Department of Psychology, City University of London, UK

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Strongly non-degenerate spontaneous parametric down-conversion

for calibration of terahertz-wave detectors

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The correlated photons in pairs generated via spontaneous parametric down-conversion (SPDC) may address completely different spectral ranges. We study the strongly non-degenerate SPDC wherein the signal photon frequency ω_s is close to an optical pump frequency ω_p so that the idle frequency $\omega_i = \omega_p - \omega_s$ hits the terahertz (THz) range. The main complicating factor for generating the non-classical field states in the THz range is a high noise level due to thermal radiation at room temperatures. Nevertheless, certain quantum-optical technologies are applicable also in this case. It was shown several years ago [1] that the SPDC-based method of D.N. Klyshko, proposed first for absolute calibration of the spectral brightness of optical sources [2], can be used for the terahertz-wave radiation in spite of the presence of the thermal noise background. In the initial Klyshko's approach the spectral brightness of quantum field fluctuations ($N_{vac} = 1$ photon per mode or $B_{vac} = \hbar\omega_i^3 / 8\pi^3 c^2$ in radiometric units) is considered as a built-in brightness reference. Classical thermal fluctuations contribute to both noise Stokes and anti-Stokes signals of a parametric terahertz-to-optical frequency converter when it operates in nonlinear-optical THz-wave detection mode. Impact of thermal fluctuations can be separated from the authentic SPDC signal when the same THz-wave input radiation makes contributions to the difference-frequency (Stokes) and sum-frequency (anti-Stokes) conversion signals.

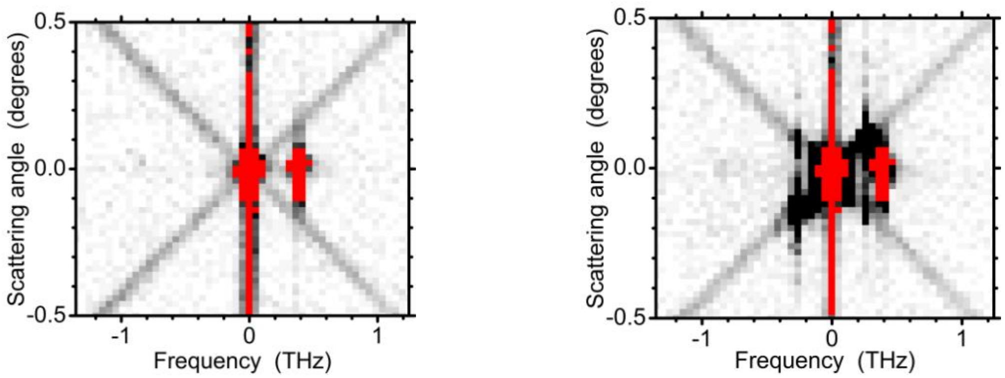

Figure. **Left:** Frequency-angular spectra of the optical signal photons generated under SPDC in strongly frequency-non-degenerate regime. Vertical (red) line in the center corresponds to the residual, elastically scattered pump radiation. Negative frequencies denote idle frequencies in the Stokes ($\omega_s = \omega_p - \omega_i$) range, positive ones denote idle frequencies in the the anti-Stokes ($\omega_s = \omega_p + \omega_i$) range. Bright (red) spot to the right from the pump line is an artifact caused by the argon discharge line. **Right:** Same, but with the external terahertz-wave source turned on. Detected are the fundamental wave (0.14 THz) and the second harmonic radiation (0.28 THz) of the backward-wave oscillator.

Now we report on the results of the experimental simultaneous observation of all the parametric optical signals related to terahertz-wave detection in a continuously pumped nonlinear-optical crystal [3]: signals due to up-conversion of the incident THz radiation to the Stokes and anti-Stokes optical ranges, due to up-conversion of the thermal noise to the both ranges and due to SPDC in the Stokes part of the optical signal spectrum (Fig.). To avoid the different influence of the idle absorption effects, we have detected THz radiation in the frequency range 0.120-0.300 THz where Mg:$LiNbO_3$ crystals used for parametric frequency conversion can be considered as practically transparent. Nevertheless, it became clear that this is not enough for estimating the SPDC-calibration as an absolute procedure in the THz range. In case of strongly non-degenerate SPDC one has to take special care for the single-mode character of the parametric interaction. Transverse spatial limitation of the nonlinear interaction volume in a crystal (mostly due to a pump beam focusing) leads to increase of a number of idle modes which can contribute to a single mode of an output signal. This number grows considerably when the frequency relation ω_i / ω_s is going down. All the idle modes are well-filled by classical and quantum fluctuations forming the background signals of the thermal up-conversion and SPDC, but cannot be filled uniformly by an incident THz radiation. The filling factor has to be taken into account in the SPDC calibration of any energy characteristic of the input radiation. Results of theoretical calculations of the filling factor, made for differently focused Gaussian pump beams and different geometries of the parametric THz up-conversion schemes, will be discussed.

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Optimal Quantum Metrology of Distant Black Bodies

(Invited talk)

Mark E. Pearce, Earl T. Campbell, and Pieter Kok

Measurements of an object's temperature are important in many disciplines, from astronomy to engineering, as are estimates of an object's spatial configuration. We present the quantum optimal estimator for the temperature of a distant body based on the black body radiation received in the far-field. We also show how to perform quantum optimal estimates of the spatial configuration of a distant object, i.e. imaging. In doing so we necessarily deal with multi-parameter quantum estimation of incompatible observables, a problem that is poorly understood. We compare our optimal observables to the two mode analogue of lensed imaging and find that the latter is far from optimal, even when compared to measurements which are separable. To prove the optimality of the estimators we show that they minimise the cost function weighted by the quantum Fisher information-this is equivalent to maximising the average fidelity between the actual state and the estimated one.

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Information transfer during the universal gravitational decoherence

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Recently Pikovski et al. have proposed in [I. Pikovski, et al. Nature Phys. 11, 668 (2015)] an intriguing universal decoherence mechanism, suggesting that gravitation may play an important role in the quantum-to-classical transition.

Here we analyze information transfer induced by this mechanism. We show that generically, on the short time-scales, gravitational decoherence leads to a redundant information encoding, governed by the energy dispersion and the Fisher information.

This leads to a objectivization of the center-of-mass position in the gravitational field. As an example we study thermal coherent states and show certain robustness of the effect with the temperature.

Finally, we draw an analogy between our objectivization mechanism and the fundamental problem of point individuation in General Relativity as emphazised by the Einstein's Hole argument.

Higher-order squeezing oscillations of the single-mode cavity field interacting with a three-level radiator

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We investigate interaction between a three-level equidistant radiator (atom, molecule) and the single-mode cavity field. In present two-photon Jaynes-Cummings model the dipole moment matrix transition elements between the adjacent energy levels d_{12} and d_{23} are supposed to be different. Moreover, in our model three-level atom is localized in optical cavity in the ground vibrational state, in which vibrational quantum number $\langle n_v \rangle = 0$.

We have assumed that three-level atom is placed in given position of the standing wave of cavity. Based on modern optical achievements it is possible to localize a small number of emitters (atoms, ions, molecules) in various geometrical systems like optical cavities, quantum dots, optical lattices and dielectric or disordered media.

In proposed model at initial moment $t = 0$ three-level atom is prepared in the first excited state $|e_1\rangle$ and quantized cavity field in squeezed vacuum state $|\xi\rangle$. By using exact analytical solution for state-vector of the coupled atom-field system found with the help of Schrodinger equation quantum-statistical properties of the quantized cavity field are examined as a function of the $|\xi|$ and $\alpha = d_{23}/d_{12}$ parameters. Much attention is devoted to the amplitude-squared squeezing of the quantized cavity field [**?**]. In this situation higher-order squeezing of cavity field has the tendency towards oscillations, but exact periodicity of these oscillations is violated by the analogy with the micromaser model [**?**] and second-order squeezing in two-photon JCM of a three-level atom [**?**].

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Nonlinear Infrared Spectroscopy

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We realize a new method of infrared (IR) spectroscopy, which uses well-developed components for the visible light. The technique relies on the nonlinear interference of correlated photons, produced via spontaneous parametric down-conversion (SPDC) in a nonlinear crystal. Visible and infrared photons are split into two channels and reflected back to the crystal, resembling a conventional Michelson interferometer. The observed interference of visible photons depends on phases of all three interacting photons: pump, visible and infrared. We insert a sample into the path of an infrared photon and infer sample's transmission coefficient and the refractive index in the infrared range from the interference pattern for the visible photon. The method does not require the use of expensive and inefficient IR detectors and sources, it can be applied to a broad variety of samples, and it does not require *apriori* knowledge of sample properties in the visible range.

Time-dependent quantum correlations in phase space

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The determination of nonclassical effects, such as squeezing and entanglement, is a challenging but unavoidable task to employ these phenomena in future technologies. However, most approaches are restricted to single-time quantum effects, albeit it is well-known that there exist quantum effects, e.g., photon anti-bunching, where one needs to correlate at least two times. To uncover the dynamics of nonclassicality, the treatment of multi-time nonclassicality is therefore a desirable aspect to be studied.

A possible approach to infer space-time nonclassicality was introduced in Ref. [1] by defining a generalized version of the well-known Glauber-Sudarshan P function [2, 3], called P functional. This multi-time-dependent functional enables a full treatment of temporal correlations in its general and closed form. Unfortunately, the P functional's Fourier transform, which is always a well-behaving function that can be used to derive nonclassicality criteria including multiple points in time [4], might be an unbounded function. In the latter case the functional itself is highly singular and therefore not observable in experiments.

A regularization approach concerning the P function was introduced in 2010, which suppresses the increase of the Fourier transform of P [5]. In contrast to the single-time case, the multi-time scenario exhibits substantial differences regarding the general behavior of involved quantities. For example, the slope of the Fourier transform of the P functional increases stronger than in the single-time case. Those and related problems are basically caused by temporal correlations which are present due to non-equal-time commutators of the field operators. The study of such and related commutator algebras is a sophisticated problem itself and needs a careful treatment to understand the subject of temporal correlations. Based on the regularization approach in [5], we introduce a method which effectively filters the multi-time-dependent P functional [6]. The presented technique overcomes the mentioned issues and applies to arbitrary interaction dynamics.

In conclusion, our approach yields novel possibilities to visualize general multi-time-dependent quantum correlations in phase space. Moreover, we present a measurement scheme and derive pattern functions to sample the regularized P functional from experimental data.

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The NV-center in nanodiamond as an absolute single-photon source

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ABSTRACT

An absolute single-photon source developed at PTB is reported on. The source is based on a nitrogen-vacancy center in a nano-diamond. It was characterized in terms of its absolute spectral photon flux per wavelength, spectral power distribution and second order correlation function. The characterization was carried out using a low-noise optical flux detector, traceable to the cryogenic radiometer; a calibrated spectroradiometer, traceable to the blackbody radiator and a Hanbury-Brown Twiss interferometer, respectively. Total single-photon fluxes between 55 fW and 75 fW, which corresponds to 190 000 photons per second and 260 000 photons per second, were obtained. The purity of the single-photon emission depends on the applied excitation power: for low excitation powers, an almost pure single-photon emission is observed ($g^{(2)}(t = 0) = 0.10$) 1.05 mW $g^{(2)}(t = 0) = 0.23$. However, even for higher excitation power the NV-center still acts like a non-classical photon emitter.

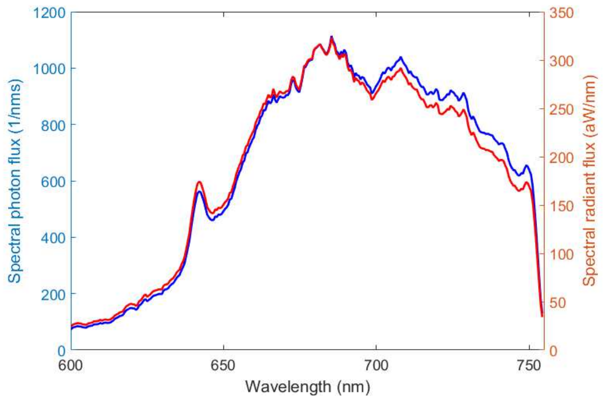

Figure 1: Absolute spectral photon flux per wavelength (blue line) and absolute spectral radiant flux per wavelength (red line).

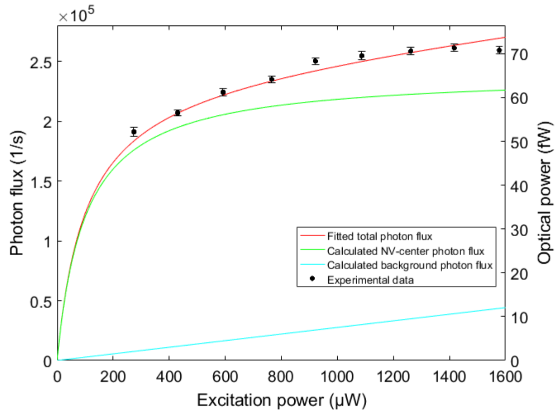

Figure 2. Total number of photons (left axis) and corresponding total optical power (right axis) of the NV-centre as a function of the excitation power of a 532 nm laser The red, green and blue curves are the total photon flux, the NV-center photon flux and the background photon flux, respectively.

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Anomalous quantum correlations of squeezed light

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Abstract: It is of fundamental interest if the outcome of an optical experiment can be interpreted in the framework of classical statistical electrodynamics, or if a quantum description is necessary. A possible way to certify nonclassical effects is based on moments of a single observable, as, e.g., quadrature squeezing [1, 2] or sub-Poisson statistics [3], which was demonstrated in plenty of experiments. In contrast, anomalous moments composed of non-commuting observables are hard to access experimentally. An important example is the correlation of intensity and field strength noise, as it unifies the particle and wave nature of quantum light. We report on the simultaneous detection of three (up to fourth-order) moments of the field fluctuations, namely noise moments of field strength, intensity, and their correlations [4]. For this purpose a homodyne cross correlation measurement [5] is implemented by superimposing the signal field and a weak local oscillator on an unbalanced beam splitter. The relevant information is obtained via the intensity noise correlation of the output modes. By varying either the local oscillator phase or intensity, we separate the respective moments from each other. In this regard, detection details like quantum efficiencies or uncorrelated dark noise are meaningless for our technique. Yet unknown insight into the quantumness of squeezed light is retrieved from the anomalous moment, correlating field strength with intensity noise. Remarkably, anomalous quantum correlations are present in a significantly wider range of the optical phase than the common squeezing effect. This property makes our method especially promising for the observation of quantum effects in the case of strong squeezing. As a central benefit, our demonstration of the failure of a classical explanation for the detection outcome is free of any assumptions on quantum physics, as the analysis does neither involve the quantum superposition principle nor non-vanishing commutators [6]. In contrast, the noise reduction in standard balanced homodyning for the observation of squeezing intrinsically requires quantum physics. The anomalous quantum correlations of squeezed light, which are verified for the first time, may pave the way for alternative applications of squeezed light in quantum technology, beyond squeezing.

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THREE-PHOTON SPECTROSCOPY OF LINEAR MEDIA.

Sergei Kulik

Spectral measurements in the infrared (IR) optical range provide unique fingerprints of materials which are useful for material analysis, environmental sensing, and health diagnostics. Current IR spectroscopy techniques require the use of optical equipment suited for operation in the IR range, which faces challenges of inferior performance and high cost. Here we develop a spectroscopy technique, which allows spectral measurements in the IR range using visible spectral range components. The technique is based on nonlinear interference of infrared and visible photons, produced via Spontaneous Parametric Down Conversion (SPDC). The intensity interference pattern for a visible photon depends on the phase of an IR photon, which travels through the media. This allows determining absorption coefficient and refractive index of the media in the IR range from the measurements of visible photons. The technique can substitute and/or complement conventional IR spectroscopy and refractometry techniques, as it uses well-developed optical components for the visible range.

Quantum sensing of noisy systems under dynamical control

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We review our unified optimized approach to the dynamical control of quantum-probe interactions with noisy and complex systems viewed as quantum baths. We show that this control, in conjunction with tools of quantum thermodynamics and estimation theory, may be used for inferring the spectral and spatial characteristics of such baths with high precision. This approach constitutes a new avenue in quantum sensing, dubbed quantum noise spectroscopy.

Urban QKD test for phase and polarization encoding devices

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Abstract. In this work, the results of quantum key distribution through urban fiber communication lines with the lengths of 15.3 km (7dB losses) and 30.6 km (13dB losses) are presented. We present the results obtained with the use of common "plug&play" optical scheme using phase encoding with those obtained by means of polarization encoding in newly developed one-way scheme. For phase encoding a key rate of 1,5 kbit/s with 3% QBER has been reaches, while the polarization scheme has shown key rate of 1.2 kbit/s with 3.6% QBER.

In this work, we present the preliminary results of quantum key distribution using an urban optical telecommunication fiber between two buildings in Moscow, with channel lengths of 15.3 km and 30.6 km with optical losses of 7dB and 13 dB, respectively. The quantum channel was single mode optical fiber, 30.6 km long, which was laid between two separated buildings in the city, wherein both the transmitter and the receiver were in the same building. In order to suppress light from neighboring optical channels an optical filter has been used with central wavelength of 1550.86 nm (one can find more details in the work of Kurochkin and coauthors [2]).

First quantum key distribution device, uses auto-compensating optical scheme ("plug&play"), first suggested in 2002 by Stucki et al [1]. Information is coded with random phase changes applied in the receiver's and sender's devices, correspondingly to the BB84 quantum key distribution protocol [3]. At 30.6 km, stable work of the quantum key distribution device has been demonstrated: quantum key generation rate of 1.0 kbit/s has been carried over several hours, with an average error level of 5.7 %. The optical pulse intensity at the exit of Alice's device contained average 0.18 photons per pulse; the total attenuation of the quantum channel with the spectral filter was equal to 11.7 dB. Later, we managed to implement a quantum key distribution through an optical fiber with the length of 15.3 km, while Alice and Bob were in separated buildings. In this case, we carried out a quantum key distribution with an average error level of 3.0 % at a speed of 1,5 kbit/s.

The second scheme uses polarization-encoding BB84 protocol. Fiber electro-optical $LiNbO_3$ phase modulators based on Pockels cells provide both high frequency polarization states generation for Alice and basis selection for Bob, requiring low operation voltages ($V\pi < 5V$). Proposed scheme uses only one laser source, which guarantee the indistinguishability of the pulses and active basis selection allows the system to have two single photon detectors in contrast to the four in the standard polarization encoding schemes. Active calibration technique is used to compensate polarization drifts within a 30.6 km quantum channel. The average QBER during several hours of operation is 3.6%. The average raw key generation rate is 1.2 kbit/s.

Both ID230 and self-made single-photon detectors have been used. Overall control of the electro-optic components is realized by NI PCIe-7811R installed in the PC.

Acknowledgements

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Superradiance by atoms meters apart

Kyungwon An

We present a superradiant microlaser operating with single atoms. In our experiment, a supersonic beam of barium atoms traverses a high-Q microcavity one by one in a tenth of microsecond while the atoms are pre-excited to a superposition state with the same phase. Superradiance-like lasing was observed even when at most one atom was present in the cavity at any moment. The cavity mean photon number increased approximately as the square of the mean number of atoms injected into the cavity during the cavity decay time of about a microsecond. If we unfold mirror reflections, it is as if the superradiance were achieved by atoms more than 30 meters apart.

Quantum characterisation, verification, and validation, with quantum Hamiltonian learning

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Physical systems are often described by simplified models to allow the study and understanding of their essential features. The usefulness of a given model can depend on how closely it approximates the actual physical system, which can be gauged from the fidelity of experimental data to the model prediction [1, 2]. Unfortunately, predicting behavior for large quantum systems is intractable to classical computers [3], which raises the problem of validating underpinning models. By enhancing classical machine learning with quantum simulations, *Quantum Hamiltonian learning* (QHL) is able to efficiently validate predictions for quantum systems given by model Hamiltonians [4]. We have experimentally demonstrated QHL using a programmable quantum simulator in silicon-photonics [5, 6] to learn the dynamics of the electron spin in a diamond nitrogen-vacancy centre [7]. This points the way to a new general approach for quantum characterization, verification and validation.

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Sub-Shot-Noise Wide Field Microscopy

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In the last years several proof of principle experiments demonstrated the advantages of quantum technologies with respect to classical schemes in imaging, metrology and sensing. The present challenge is to overcome the limits of proof of principle demonstrations to approach real applications. We present recent results on the estimation of transmission/absorption coefficient with true and significant quantum enhancement, exploiting spatially multi-mode non-classical photon number correlations in twin beams [1,2]. The use of multimode correlation allows to realize wide field imaging in which the whole absorption profile of a weakly absorbing object is retrieved in one shot. In particular, a sub-shot-noise (SSN) wide field microscope is implemented [3], delivering the best sensitivity per photon obtained up to now in absorption measurements. More in detail, the microscope produces real-time images of 8000 pixels at full resolution, for $(500\mu m)^2$ field-of-view, with noise reduced at 80% of the shot noise level in each pixel. By simple post-elaboration, specifically applying a “quantum enhanced median filter”, the noise is further reduced down to the 30% of the shot noise.

The performances achieved in [3] reach for the first time a true and significant improvement of the sensitivity with respect to any classical absorption microscopy at the same illumination level without any post-selection. Next step will be to exploit the potentialities of this system for real applications as absorption imaging of complex structures, like biological samples that can be particularly delicate or photosensitive, thus requiring low level of illumination.

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Quantum memory cell as a controllable Mach-Zehnder interferometer

A.S. Losev, T.Yu. Golubeva, Yu.M. Golubev

We consider the consecutive writing of two signal quantum light pulses (squeezed in orthogonal quadratures or entangled to each other) into a four-levels atomic ensemble of tripod-type configuration (Fig. 1). Then, a transformation their images inside a medium, and next, reading out them. We applied the high-speed quantum memory protocol [1, 2] for the writing and subsequent reading. In this case, the interaction of radiation and medium occurs on a time scale much less than a lifetime of the excited state 4. Using the approximation of motionless atoms allows neglecting the Doppler broadening and collision decoherence of quantum states. For the consecutive writing and reading of a pair of signal pulses, one can use different combinations of two classical driving pulses Ω1, Ω2: their simultaneous and sequential usage. The interaction is considered resonant. We use the paraxial approximation of pulses propagation along one selected axis.

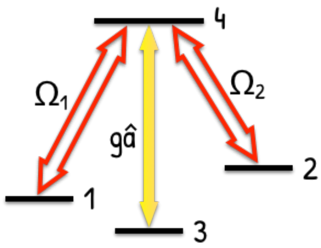

Fig. 1. Tripod atomic configuration of levels and transitions. Ω_1, Ω_2 are Rabi frequencies of driving fields, g is the interaction constant, $\hat{a}$ is annihilation operator of the signal field.

Two atomic coherences form as a result of the consecutive writing of two signal pulses. One coherence couples state 1 and 3 and the other 2 and 3. The reading can be done directly from them, or also from their linear combinations. That makes it possible to draw an analogy between quantum tripod memory and Mach-Zehnder interferometer (Fig. 2).

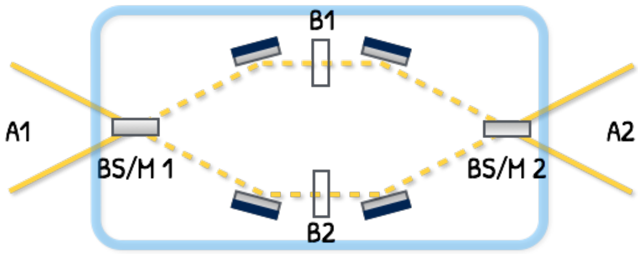

Fig. 2. The analogy between the tripod-type quantum memory cell and the Mach-Zehnder interferometer. A1 and A2 are two pairs of sequentially incoming and sequentially outgoing signal pulses. BS/M 1 and BS/M 2 is the pair of beamsplitters or fully reflecting mirrors. B1 and B2 are atomic coherences or their linear combinations which storage mapped states of light pulses.

In this analogy, every beamsplitter (input and output) is replaceable in a mirror with a reflective coefficient of 100%. It depends on how driving pulses are used during the writing and reading processes, simultaneously or sequentially.
Thus, pulse application variability gives an opportunity to get the pair of orthogonally squeezed pulses or the pair of entangled pulses on demand.
Besides, on the storage time, various manipulations which change quantum states can be carried out with atomic coherences. These are similar to manipulation by light beams inside the Mach-Zehnder interferometer. For instance, in the protocol of dense quantum coding [3].

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Ultimate precision of adaptive noise estimation

Stefano Pirandola and Cosmo Lupo

We consider the estimation of noise parameters in a quantum channel,assuming the most general strategy allowed by quantum mechanics.
This is based on the exploitation of unlimited entanglement and arbitrary quantum operations, so that the channel inputs may be interactively updated.
In this general scenario we draw a novel connection between quantum metrology and teleportation.
In fact, for any teleportation-covariant channel (e.g., Pauli, erasure, or Gaussian channel), we find that adaptive noise estimation cannot beat the standard quantum limit, with the quantum Fisher information being determined by the channel's Choi matrix.
As an example, we establish the ultimate precision for estimating excess noise in a thermal-loss channel which is crucial for quantum cryptography.
Because our general methodology applies to any functional which is monotonic under trace-preserving maps, it can be applied to simplify other adaptive protocols, including those for quantum channel discrimination.
Setting the ultimate limits for noise estimation and discrimination paves the way for exploring the boundaries of quantum sensing, imaging and tomography.

Ultimate Precision of Adaptive Noise Estimation

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Multipartite entanglement enhances quantum key distribution in networks

Chiara_Macchiavello

The laws of quantum mechanics allow for the distribution of a secret random key between two parties.
We analyse the security of a protocol for establishing a common secret key between N parties (i.e. a conference key), using resource states with genuine N-partite entanglement.
We compare this protocol to conference key distribution via bipartite entanglement, regarding the required resources, achievable secret key rates and threshold qubit error rates. We discuss quantum networks with bottlenecks for which our multipartite entanglement-based protocol can benefit from network coding, while the bipartite protocol cannot.

Quantum time mechanism: towards a quantum spacetime

V. Giovanetti, S.Lloyd, L. Maccone

We give a mechanism to construct a quantum spacetime by evaluating space and time through quantum rods and clocks. It provides a framework to treat time and space as homogeneous degrees of freedom, deals with quantum superposition and quantum interference in time, and gives a fully quantum prescription for measuring the time-of-arrival of particles and the time of arbitrary events. Our quantum spacetime uses the conditional probability amplitudes framework of Page and Wootters for time, and we extend a proposal of Piron for space.

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ANALYTICS OF QUANTUM PHYSICS

Eugene MACHUSKY

The first attempt to develop absolute metric system of physical units was made by Gauss at the beginning of nineteenth century. The attempt was unsuccessful because of the inconsistency of hyperbolic and elliptic geometry. Application of parabolic and logarithmical bonds of transcendental numbers PI and E gives the possibility to solve the problem of geometrical inconsistency and completely to coordinate the values of fundamental quantum constants. All constants, in fact, these are quasi-harmonic gradients of functions of normal and log-normal distribution of inverse geometrical parameters of the spiral which pulsates from zero to infinity relatively perimeter PI*E.

Two equations constitute basis of electrodynamics of Maxwell-Gauss: C = (R +4*PI*C/10^18) ^ 64*10^7 = 299792457.867591338433684, R = Integer[10^8*(C/10^7) ^ (1/64)]/10^8 = 1.05456978. C it is the rotational speed of radius-vector. R it is the inverse squared radius. 4*PI it is solid angle in radians. 4*PI*10^-7 it is Magnetic constant. 4*PI*C*10^-7 it is Impedance of free space. 1/(4*PI*10^-7)/C^2 it is Electric constant. Value C it is Speed of light in physics, but arithmetically it is simply number of turns around a ball with radius 4*PI/10^18 during a unit of time. Three equations constitute basis of thermodynamics of Kelvin-Avogadro: K = E +AS +BS = 2.7315999984590452. AS = 1/100/Sum {[137 + {137 100) *n]/10^(3*n+2) = 1/100/ (1.11111111111...) ^3 = 0.00729. BS = Sum [602214183/10^ (3*n +8)] = 0.00602816999999...999999397183 = 0.00602817. Value K (kelvin) it is upper limit of inverse temperature. Value E it is base of natural logarithm in mathematics but in physics it is lower limit of inverse temperature. Decimal fractions AS and BS have linked the alphabet (0...1) and alphabet (0...9) because 1= 0.999999... and 10 = 9.99999... Digital sequence B = 602214183 it is integer of Avogadro. Digital sequence NB = 0.006022141073 = B/ (1 +4*PI/10^8)/10^11 geometrically binds PI and B.

Mutual bonds of geometrical parameters of rotating spiral can be described by one expression: [G] = 2*PI*[R]*{1 +[A]} where [R] presents matrix of relative inverse radii, [A] it is matrix of eccentricity. The instant values of Ri, Ai are linked by the parameter of information entropy sqrt(2*PI*E) of normal distribution: Ri = 1 +2/100*(E +Ai*(1 +sqrt(2*PI*E)/10)). Inverse eccentricities concentrate near reciprocal value of squared sum of mean values of numbers PI and E (root mean square, arithmetical mean, geometrical mean, harmonic mean): {sqrt[(PI^2+E^2)/2] +(PI+E)/2+sqrt(PI*E) +2*PI*E/(PI+E)} ^2= 136.9938985020083597. Equation PI*10^59 = E^136.9972503724980956 illustrates the coupling by exponent. The finite difference of these digital sequences generates the entropy of inverse calculations with floating point near 12 decimal place of mantissa. It corresponds to entropy of Rydberg constant.

Comparison of CODATA constants with the values analytically derived:

Speed of light 299792458
299792457.86759134 Background temperature 2.725
2.7252543275634558 Relative molar mass 0.012
0.0119992777505492 Kelvin 2.7316
2.7315999984590452 Fine structure constant
0.0072973525664(17) 0.0072973525205056 Avogadro
constant 6.022140857(74)
6.0221410564201849*10^23 Boltzmann constant

1.38064857(74)	1.3806484502310000*10^-23	Planck constant
6.626070040(81)	6.6260700111158522*10^-34	Elementary charge
1.6021766208(98)	1.6021766150248797*10^-19	Gravitational constant
6.67408(31)	6.6740529112548490*10^-11	

Functional bonds of two transcendent numbers PI and E give the possibility to evaluate all fundamental constants of quantum physics with practically unlimited accuracy 1/10^64. In fact, Quantum dynamics it is two-dimensional image of three-dimensional motion of wave front. Quantum physics it is digital bridge between continuous and discrete mathematics.

Quantum channels from reflections on moving mirrors

Stefano Mancini

Abstract: We study the kind of quantum channel that arises from light reflection upon an accelerating mirror.
Two competing mechanisms emerge in such a model, namely photons production by the mirrors motion and inter-mode interference.
As consequence we find out a quantum amplifier channel or a purely classical additive channel or a quantum lossy channel depending on the considered regime.

Hidden Quantum Correlations and Entanglement in Systems without Subsystems As a Resource for Quantum Technologies

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Notion of hidden correlations for quantum and classical noncomposite systems is discussed. For the systems without subsystems, the correlations are analogs of correlations between the degrees of freedom of subsystems in multipartite systems. In view of this analogy, we study a possibility to formulate the subadditivity condition and the strong subadditivity condition for classical probability distribution of one random variable and for single spin (single qudit) density matrix, which are known for bipartite and tripartite systems but unknown for noncomposite systems. The notions of mutual information and conditional mutual information, which are nonnegative characteristics of hidden correlations in systems without subsystems, are suggested and investigated as analogs of these notions known for bipartite and tripartite systems, respectively. We present the subadditivity condition on examples of qutrit (three-level atom) density matrix and two qubit density matrices associated with the qutrit density matrix, as well as on the example of the five-level atom. New information-entropic inequalities for quantum tomographic probability distributions describing the qudit states are demonstrated. Within the framework of the star-product quantization approach, we review different schemes of quantum tomography like optical tomography, symplectic tomography, and center-of-mass tomography. The relation of these tomographies with the Wigner function description of quantum states is elucidated. The description of quantum observables (Hermitian operators) by probability distributions is discussed. A possibility of the experimental check of hidden quantum correlations and Bell correlations for artificial n-level atoms in studying the superconducting circuits based on Josephson junctions is considered. The relation of hidden correlations with entanglement properties of artificial atoms described by qudit tomograms is clarified.

The separability property in confined quantum systems

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A simple system of two particles in a bidimensional configurational space S is studied. The possibility of breaking in S the time independent Schrödinger equation of the system into two separated one-dimensional one-body Schrödinger equations is assumed. In this paper, we focus on how the latter property is countered by imposing such boundary conditions as confinement in a limited region of S and/or restrictions on the joint coordinate probability density stemming from the sign-invariance condition of the relative coordinate (an impenetrability condition). Our investigation demonstrates the reducibility of the problem under scrutiny into that of a single particle living in a limited domain of its bidimensional configurational space. These general ideas are illustrated introducing the coordinates X_c and x of the center of mass of two particles and of the associated relative motion, respectively. The effects of the confinement and the impenetrability are then analyzed by studying with the help of an appropriate Green's function and the time evolution of the covariance of X_c and x. Moreover, to calculate the state of the single particle constrained within a square, a rhombus, a triangle and a rectangle the Green's function expression in terms of Jacobi θ_3-function is applied. All the results are illustrated by examples.
The report is based on the article [1].

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Dynamical vector fields on the manifold of quantum states I

Giuseppe Marmo

Abstract: For finite systems, quantum states are a subset of the manifold of Hermitian operators. The positivity condition on states requires the subset of states to be a manifold with corners.
The normalization condition restricts the positive operators to the affine subspace of unit trace operators.
The presence of corners requires suitable care to deal with differential calculus ,Poisson tensors and Jordan tensors.
We shall introduce Hamiltonian ,gradient and Kraus vector fields to deal with Markovian and non-Markovian evolution.

Simulating stroboscopic non-Markovian evolution of quantum systems

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The simulation of non-Markovian dynamics and the test of its main features hve been object of several experimental works in the last years, with relevant examples mainly based on the use of all-optical systems.

I will describe the behaviour of a multipass displaced Sagnac interferometer conceived to simulate with photons the stroboscopic evolution of quantum systems in both the Markovian and non-Markovian regimes.

The theoretical and experimental results obtained in the cases of single qubit and two photon entangled state evolution will be presented.

SiC single photon sources for applications in quantum information science

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Single photon sources (SPSs) that are bright, stable, efficient and ideally operate at room-temperature, producing single photons on-demand are critical components needed for advancements in quantum information science. [1] Indistinguishability of the emitted photons is also an important requirement for some key applications. Solid state SPSs can offer key engineering advantages including potential for scalability, compatibility with existing electronics industry fabrication processes and potential for systems integration. These sources include quantum-dot (QD) based systems and defect centres in solid state materials exhibiting atom-like optical transitions. The QD-based SPS systems represent the highest level of achievement thus far in terms of performance and sophistication of engineering but at present these performance characteristics are restricted to cryogenic temperatures. The nitrogen-vacancy (NV) centre in diamond is the best known of the defect centre based single photon emitters (SPEs) but engineering of structures and microelectronic devices in diamond is challenging. Single photon emitters have also been recently identified in SiC and there is growing recognition that SiC is an attractive host material for integration of SPSs, waveguides and detectors into a single platform for quantum information processing. [1] Its high refractive index provides strong confinement of the optical mode for waveguide structures and it has excellent thermal and mechanical properties allowing robust and stable optical structures to be formed. It also has non-linear optical properties suitable for functionalities such as optical switching. These attributes coupled with its maturity as a material for fabrication of microelectronic devices add to its attraction as a platform for quantum optical device integration. We have made considerable progress in the development of SiC single photon sources and in this presentation, in addition to our work on identification of SPEs in SiC, we will present our work on development of a bright electrically-driven single photon source in SiC operating at room temperature. [2] We have also demonstrated controlled formation of ultra-bright, fully polarized SPEs in SiC using device-engineering compatible oxidation and etching techniques [3] and most recently we have developed and demonstrated a novel technique for targeted fabrication of optical micro-resonators at the locations of pre-characterized single photon emitters. [4] These are important steps toward developing optimal coupling between optical cavity structures and SPEs and provide a sound foundation for our future work toward development of a practical single photon source for applications in quantum information science.

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Quantifying the backflash radiation for quantum key distribution

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Quantum key distribution (QKD) [1, 2] is a technique for sharing secret cryptographic keys between two parties (Alice and Bob), considered the only absolute secure way to encrypt and protect data, since security is ensured by the laws of physics. However, the security of practical systems (as any other cryptographic system) strongly depends on their device implementations. Deviation of QKD devices from their theoretical model can be exploited as side-channels or a back-doors [3, 4].
We present results [5] obtained in the characterization of backflash emission in commercial InGaAs/InP single photon detector operating at telecom wavelength [6], used in most of the QKD systems. The exploitation of backflash light is a serious security breach in a poorly designed QKD system.
We characterize such backflash light in gated InGaAs/InP SPADs and discuss its spectral and temporal characterization for different detector models and different operating parameters. We qualitatively bound the maximum information leakage due to backflash light and propose solutions for preventing such leakage.

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Single Ion Implantation: An important tool for fabrication of quantum devices based on NV-centers

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The key technology to fabricate quantum devices is the addressing of single atoms in a solid with high lateral resolution. Whereas the manipulation of single atoms at the surface is possible since several years, a three-dimensional addressing in the bulk requires more effort. Low energy ion implantation allows addressing single countable atoms inside a given solid bulk material with nanometer precision. To meet this goal it is necessary to focus or collimate the ion beam and secondly to count the ions. The presented approach is to detect an ion on the fly by mirror charge detection and to focus the ion using a modified commercial FIB system. The use of ion traps is an alternative method to fulfill this requirement. Using overgrowth of CVD diamond three-dimensional structures can be produced. However, significant progress is still required, before properly functioning quantum devices can be fabricated.
Besides the technical challenge of implanting a counted number of ions with nanometer precision, the deterministic creation of NV-centers is an additional requirement that has to be considered: The implanted nitrogen atom has to be converted into an NV-center with a creation efficiency of almost 100%. Unfortunately, the creation of a vacancy in the diamond by the ion impact is a statistical process and therefore not deterministic. Furthermore, the NV-center has to be converted into a negative charge state.
The talk will discuss the state of the art of single ion nanoimplantation methods as well as new developments in material science to overcome the NV-center creation problem.

Vector Potential Quantization in QED and the Photon intrinsic properties

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Abstract. We enhance here the vector potential amplitude quantization at a single photon state beyond the standard description in QED. The analysis of the general solution of the vector potential obtained by resolving Maxwell's equations implies that its amplitude $\alpha_0(\omega)$ is proportional to the angular frequency, so that for a monochromatic *k*-mode we can write $\alpha_{0k}(\omega) = \xi\omega_k$, where ξ is a constant, $|\xi| \approx 1.747\ 10^{-25}\, Volt\ m^{-1} s^2$. The fundamental physical quantities characterizing the wave-particle nature of a single *k*-mode photon: energy E_k and momentum $\vec{p}_k$ (particle), vector potential amplitude α_{0k}, wave vector $\vec{k}$ and dispersion relation (wave), are related to the angular frequency ω_k

$$\frac{E_k}{\hbar} = \frac{|\vec{p}_k|}{\hbar / c} = \frac{\alpha_{0_k}}{\xi} = |\vec{k}|c = \omega_k$$

In the plane wave representation the vector potential $\vec{\alpha}_{k\lambda}(\vec{r},t)$ can be written as: $\vec{\alpha}_{k\lambda}(\vec{r},t) = \omega_k \left\lfloor \xi \hat{\varepsilon}_\lambda\, e^{i\left(\vec{k}\cdot\vec{r} - \omega_k t + \theta\right)} + cc \right\rfloor$, with the polarization λ =1,2 (corresponding to Left and Right hand circular), $\hat{\varepsilon}_\lambda$ the polarization unit vector, θ a phase parameter, $\vec{k}$ the wave vector and *cc* the complex conjugate. Obviously, $\vec{\alpha}_{k\lambda}(\vec{r},t)$ satisfies the classical wave propagation equation in vacuum

$$\vec{\nabla}^2 \vec{\alpha}_{k\lambda}(\vec{r},t) - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\vec{\alpha}_{k\lambda}(\vec{r},t) = 0$$

It has been shown that, whatever the mode *k*, the quantized vector potential amplitude can be expressed in the wave theory as an operator $\tilde{\alpha}_0 = -i\xi c\vec{\nabla}$. We can easily demonstrate that the vector potential function $\vec{\alpha}_{k\lambda}(\vec{r},t)$ satisfies both Schrödinger's equation for the energy with eigenvalue $\hbar\,\omega_k$ and a linear time-dependent equation for the vector potential amplitude operator $\tilde{\alpha}_0$ with eigenvalue $\xi\,\omega_k$, following the coupled equation

$$i\begin{pmatrix}\xi\\ \hbar\end{pmatrix}\frac{\partial}{\partial t}\vec{\alpha}_{k\lambda}(\vec{r},t) = \begin{pmatrix}\tilde{\alpha}_0\\ \tilde{H}\end{pmatrix}\vec{\alpha}_{k\lambda}(\vec{r},t)$$

where $\tilde{H} = -i\hbar c\vec{\nabla}$ is the well-known massless field Hamiltonian.

Consequently, the vector potential $\vec{\alpha}_{k\lambda}(\vec{r},t)$ with the quantized amplitude may play the role of a real wave function for the photon in a non-local representation that can be suitably normalized. Thus, the probability $P_k(\vec{r})$ for detecting a *k*-mode photon around the point $\vec{r}$ is proportional to the square of the angular frequency

$$P_k(\vec{r}) \propto \left|\vec{\alpha}_{k\lambda}(\vec{r},t)\right|^2 \propto \xi^2\omega_k^2$$

We also deduce the amplitude $|\vec{\varepsilon}_{k\lambda}|$ of the electric field for a single *k*-mode photon

$$|\vec{\varepsilon}_{k\lambda}| = \left| -\frac{\partial}{\partial t}\vec{\alpha}_{k\lambda}(\vec{r},t)\right| \propto \xi\omega_k^2$$

which is also proportional to the square of the angular frequency.
This representation confers precise properties to a single photon state that need to be investigated experimentally.

Thermal effects on coherence and excitation transfer.

Laleh Memarzadeh

The main objective in many different areas of research is understanding and improving transport of electrons, phonons, exciton etc.. To control and utilize the transport in small scales, it is crucial to distinguish those quantum features that have actual role in it. Here we study excitation transfer in a system of qubits interacting with each other through a common bath at nonzero temperature. Our results demonstrate that depending on coherence of initial state, environment temperature affects excitation transfer in different ways. We show that when initial state is incoherent, as time goes on, coherence and probability of excitation transfer increases. But for coherent initial state, we find a critical value of temperature, below which system loses its coherence in time which diminishes the probability of excitation transfer. Hence in order to achieve higher probability of excitation transfer, temperature of the bath should be increased beyond the critical temperature. Stationary probability of excitation transfer and coherence are discussed in both cases. We also find the dependence of critical temperature on system size.

List of co-authors Azam Mani

Gaussian quantum steering of two bosonic modes in a squeezed thermal environment

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Einstein-Podolsky-Rosen steerability of quantum states is a property that is different from entanglement and Bell nonlocality [1]. We describe the time evolution of a recently introduced measure that quantifies steerability for arbitrary bipartite Gaussian states [2] in a system consisting of two bosonic modes embedded in a common squeezed thermal environment.

We work in the framework of the theory of open systems. If the initial state of the subsystem is taken of Gaussian form, then the evolution under completely positive quantum dynamical semigroups assures the preservation in time of the Gaussian form of the states [3].

In Ref. [4] it was shown that the thermal noise and dissipation introduced by the thermal environment destroy the steerability between the two bosonic modes. In the case of the squeezed thermal bath we show the dependence of the Gaussian steering on the squeezing parameters of the bath and of the initial state of the system. A comparison with other quantum correlations for the same system shows that, unlike Gaussian quantum discord, which is decreasing asymptotically in time, the Gaussian quantum steerability suffers a sudden death behaviour, like quantum entanglement.

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Landau-Zener-Stückelberg interferometry and switching quantum state of qubits in an open-multibands magnetic quantum wire

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Abstract

In this study, we investigate the quantum tunneling of a two-level multi-crossing system in an accelerating onedimensional optical parabolic potential in an open-multibands quantum two-level systems, with particular interest on the subbands $n = 0$, $n = 1$, $n = 2$ and $n = 3$ of a heterostructure 3D quantum wire. Local magnetic fields are used to coherently manipulate and control quantum bit (qubit) states. Thus, we establish the time scale dependencies of the analytic expressions of the energy eigenvalues, non-adiabatic and adiabatic transition probabilities calculated from the diabatic and adiabatic bases in any subband. If the interspin coupling is sufficiently strong, the system undergoes adiabatic Landau-Zener dynamic in a weak external field. Otherwise, for weak interspin couplings, the system undergoes nonadiabatic Landau-Zener dynamics for strong confinement in a strong external field while our system readily exhibits more multi-crossings.

The probe qubit spectrum obtained from this approach can be used to characterize the qubit evolution in a sample with a confined qubit, while at the same time it can be used to simulate the Landau-Zener-Stuckelberg interferometry process with high accuracy. Our numerical observation shows many interesting phenomena, which can be demonstrated by future experiments.

Permutation Modulation for Information Reconciliation in CV-QKD Applications

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Abstract

The main problem in continuous variable Quantum Key Distribution (QKD) is quantization and assignment of labels to the samples of the Gaussian variables observed at Alice and Bob. Unfortunately, most of the samples, assuming that the Gaussian variable is zero mean, tend to have small magnitudes and are easily disturbed by noise. Transmission over longer and longer distances increases the losses corresponding to a lower effective Signal to Noise Ratio (SNR) exasperating the problem. Here we propose to use Permutation Modulation (PM) as a means of quantization of Gaussian vectors at Alice and Bob over a d-dimensional space with ▯ $\gg 1$. The goal is to achieve the necessary coding efficiency to extend the achievable range of continuous variable QKD by quantizing over larger and larger dimensions. Fractional bit rate per sample is easily achieved using PM at very reasonable computational costs. Order statistics is used extensively throughout the development from generation of the seed vector in PM to analysis of error rates associated with the signs of the Gaussian samples at Alice and Bob as a function of the magnitude of the observe samples at Bob. Finally, a coding strategy for Reverse reconciliation at Bob based on PM is presented.

Mode analysis of higher-order transverse-mode correlation beams in a turbulent atmosphere

H. Havetisyan and C. H. Monken

Abstract:

Quantum communication, meaning the transfer of quantum states between detection/processing stations, is one of the pillars of the quantum information area. This transfer of quantum states may connect stations that are very close, as for example the logical gates inside a quantum processor, or very far apart as it may happen in quantum key distribution procedures. The reliability or even the feasibility of long distance quantum communications depends on the resilience of quantum states to deleterious effects in the communication channels.

Photons are the most convenient quantum information carriers, since they are easily generated, they can be entangled in a number of degrees of freedom, they are fairly insensitive to external noise sources, and they can be detected at reasonable rates and efficiency. Nevertheless, when propagation in open space is needed, as in ground-satellite links, entangled photon states can be degraded by the atmosphere. The main degradation factor is the atmospheric turbulence due to the refractive index fluctuations caused by the mixture of hot and cold air streams.

In this talk, we discuss the transmission of entangled two-photon Laguerre-Gaussian modes through the turbulent atmosphere and how the correlation of orbital angular momentum of photons survives the effects of turbulence.

An experiment exemplifying the time as an emergent property

Ekaterina Moreva*, Giorgio Brida, Marco Gramegna, Lorenzo Maccone, Marco Genovese*

Several theoretical papers discussed if time can be an emergent property deriving from quantum correlations. One of these is the Page and Wootters (PaW) mechanism which considers “time” as a quantum degree of freedom. In this work we give a consistent quantum description of time, based on Page and Wootters’s mechanism and describe an experimental setup to implement quantum time protocol using continuous time and two-time correlations.

Towards diamond sensing with NV centers

E. Moreva

Nitrogen Vacancy (NV) centers in nano-diamonds (ND) have many interesting characteristics that renders them promising tools for nano and quantum technology applications, these range from the realization of on-demand deterministic single-photon sources to the implementation of quantum information protocols.

In recent years, among the other appealing properties of NV-ND, their bio-compatibility has emerged with increasing evidence as well as their functionality under physiological conditions, so that they can effectively safely pass the cell membrane for intracellular biosensing purposes.

In this poster we discuss two applications

- Super-resolved imaging exploiting the nonclassical behavior of single NV centers.

- Magneto-optical detection of spins associated to NV centers in diamond for new bioimaging techniques at room temperature (preliminary results).

Towards a scalable semiconductor platform entangled/single photon emitters based on site-controlled quantum dots

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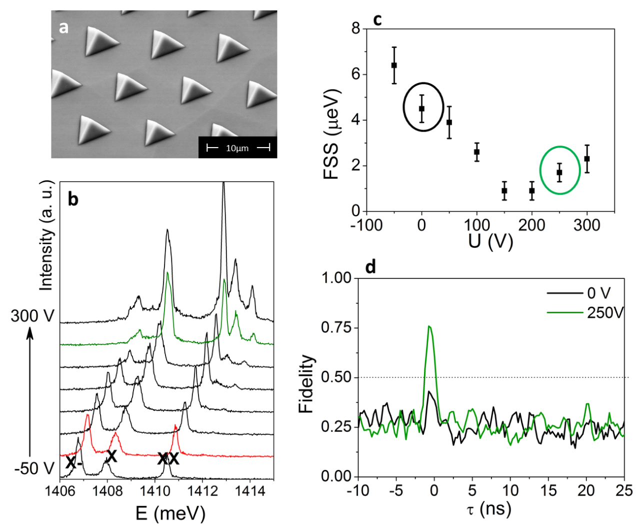

Fig. 1 a) SEM image of back-etched Pyramidal Quantum Dots; b) voltage-dependence of the spectrum c) and of the FSS as the stress is applied by means of a monolithic piezo; d) evolution/modulation of Fidelity when a voltage of 0/250V is applied.

Great progress has been obtained in the development of scalable semiconductor sources of quantum light, in view of their exploitation as unique-to-date platform for on-demand photons. Scalability, tuneability and other requirements for technological exploitation have become indeed major research topics. It is worth mentioning that from the first demonstration in 2006 [1], QD semiconductor sources have now improved their fidelity to the maximally entangled state from a modest ~0.55 to around 0.95 demonstrated in 2016 [2]. And strong progress is still expected and ongoing.

Among tuning techniques, the application of a strain field (by the exploitation of a monolithic piezoelectric cell) has shown remarkable results when applied to self-assembled systems, showing a broad tuning range (and still allowing employing a p-i-n structure to electrically control the QDs).

Pyramidal Quantum Dots (PQDs) have proven to be a promising platform for the realization of scalable sources of entanglement, which, most importantly, are position-controlled – the major advantage over the other state-of-the-art QD systems. Thanks to the intrinsic uniformity of properties of these QDs they have shown a high density of entangled photon emitters without any tuning technique [3], while electrically-driven entangled-photon emission was recently demonstrated and highlighted [4].

In our contribution we review the current progress of the PQD platform and discuss recent developments with preliminary results / *proof of concept* for the application of strain fields to our PQD system. The objective is to eliminate typically statistically small QD asymmetry, wavelength dispersion related issues, and further increase the density of entangled and, eventually, indistinguishable photon emitters [5]. *As from Fig. 1, the FSS of PQDs was also tuned and corrected to ~0μeV and modulation and restoration of a "high" entanglement was demonstrated for the first time (Fig.1).* This paves the way to the realization of a site-controlled source of entangled photons where virtually any QD can be tuned by employing for example 3 independent uniaxial stresses, as previously proven on self-assembled QDs [6]. Resonant pumping will finally be required to obtain also indistinguishable emission.

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Transfer Matrix Reformulation of Scattering Theory in Two Dimensions and Its Applications in Optics

Ali Mostafazadeh (Mustafazade)

We outline an alternative to the S-matrix formulation of scattering theory in two dimensions that relies on a multidimensional notion of transfer matrix. This allows for an exact solution of the scattering problem for delta function potentials in two (and three) dimensions and paves the way for establishing a genuinely multidimensional generalization of unidirectional invisibility and the Lorentz reciprocity principle. The latter implies that in dimensions other than one the reciprocity principle does not prohibit nonreciprocal transmission. This is of particular significance for constructing linear optical and acoustic diodes, which was previously considered impossible. We offer a number of concrete physical applications of our general results. In particular, we construct a physical model for an active optical wire that is invisible from one direction but scatters light coming from the opposite direction. If time allows we report the application of our formulation in providing the exact solution of a class of nontrivial two-dimensional scattering problems with direct optical applications.

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Interpretation miniatures

Hrvoje Nikolic

Abstract:
Most physicists do not have patience for reading long and obscure interpretation arguments and disputes.
Hence, to attract attention of a wider physics community, in this talk various old and new aspects of quantum interpretations are explained in a concise and simple (almost trivial) form.
About the ``Copenhagen" interpretation, we note that there are four different versions of it and explain how to make sense of ``local non-reality" interpretation.
About the Bohmian interpretation, we explain that it is analogous to dark matter, use it to explain that there is no big difference between non-local correlation and non-local causation,
and use some condensed-matter ideas to outline how non-relativistic Bohmian theory could be a theory of everything.
We also explain how different interpretations can be used to demystify the delayed choice experiment, to resolve the problem of time in quantum gravity, and to provide alternatives to quantum non-locality.

Generalised Echoes for Robust, Optimal Quantum Enhanced Metrology

Samuel Nolan

Quantum metrology aims to exploit quantum correlations in order to estimate a classical parameter with precision beyond the classical limit. Spin-squeezing is a well known technique to generate and exploit these correlations in interferometers where the total number of particles is constrained, for instance matter-wave interferometers. However, quantum parameter estimation theory reveals that the estimation precision is bounded by the quantum Fisher information, known as the quantum Cramer-Rao bound (QCRB). Measurement schemes which achieve this precision are said to saturate the QCRB, and are optimal. Typical spin-squeezing experiments do not saturate the QCRB, indicating that hard earned quantum correlations are going to waste. In addition to this, quantum enhanced interferometers are particularly sensitive to sources of loss and noise, particularly finite number detection resolution. There has recently been a great deal of work regarding echo protocols, whereby a period of unitary evolution is applied to the state after the state has passed through the interferometer. These have been shown to robustify the state against finite number detection resolution, and allow the QCRB to be reached via a projective measurement. We show that if one has access to the full probability distribution of a state the sensitivity is guaranteed to saturate the QCRB under some modest conditions, which are easily met in typical spin-squeezing experiments, without requiring an echo. Although not necessary, including an echo does not affect this result, and we explore the robustness of the classical Fisher information to finite number detection resolution under a number of echo schemes. We find schemes that provide more robustness than an echo, and show that a GHZ state may be detected at the Heisenberg limit, even in the presence of significant detection noise.

Homodyne-like detection via photon-number-resolving detectors: from coherent states discrimination to quantum cryptographic applications

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Homodyne detection plays a central role in quantum information processing with continuous-variable optical states. However, sometimes accessing the statistics of detected light, which is connected to the particle-like nature of light, could also be useful. Unfortunately, in a standard homodyne scheme the use of a high-intensity local oscillator (LO) prevents the possibility to operate in the photon-number-resolving (PNR) domain. On the other hand, PNR detectors are limited to detect up to tens of photons and, therefore, cannot be employed in a typical homodyne detection setup.

Here we propose and implement a photodetection scheme that takes advantage of the characteristics of both standard homodyne and PNR detectors [1]. Our setup is based on the usual interferometric homodyne detection scheme, but with a relatively low-intensity LO and with PNR detectors instead of pin-photodiodes. The detectors can resolve the photon numbers at the two outputs of the interferometer and their difference can be evaluated. Therefore, we can obtain information about the phases through the interferometric part of the detection scheme, whereas the PNR detectors provide the statistics of light, which can be used to better characterize the detected signals.

We apply our scheme to the discrimination between two phase-shifted coherent states affected by either uniform or Gaussian phase noise, performing a proof-of-principle experiment. The number of photons at the two outputs is measured with two hybrid photodetectors and ~~is~~ used in post processing to calculate the shot-by-shot photon-number differences. The performance of the discrimination strategy is quantified in terms of the error probability of discriminating the noisy coherent signals as a function of the characteristic noise parameters. Moreover, the hybrid photodetectors allow us to explore a wide photon-number dynamic range, also making the detection apparatus useful to investigate different regimes of LO intensity.

We finally discuss the possibility to apply the new detection scheme to a quantum key distribution protocol based on coherent states [2] considering, as figure of merit, the mutual information between sender, receiver and eavesdropper, in the presence of individual attacks [3].

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Random symmetric states for robust quantum metrology

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In this work we conduct a systematic study by analyzing typical properties of the *quantum* and *classical Fisher information* on various ensembles of quantum states [1]. In what follows we present the summary of the most important results. The full version of the work can be found in Ref. [2].

a. Futility of general random states. We prove that Haar-random pure states states of distinguishable particles ($\mathcal{H} = \left(\mathbb{C}^d\right)^{\otimes N}$) are typically *not* useful for metrology, despite them having a large amount of entanglement as measured by the entanglement entropy [3]. This holds even if we allow for local unitary optimization of the input states.

b. Usefulness of random symmetric states. We show that, on the contrary, typical pure states from the *symmetric* (bosonic) subspace of $\mathcal{H}$ of any local dimension achieve Heisenberg scaling for any fixed hamiltonian encoding. Moreover, we prove that the usefulness of random symmetric states is robust against loss of a fixed number of particles, and holds also for mixed states with fixed spectra (as long as the distance from the maximally mixed state in the symmetric subspace is sufficiently large). This is in contrast to the case of GHZ states, which completely lose their (otherwise ideal) phase sensitivity upon loss of just a single particle. Thirdly, we show that, even for a fixed measurement, random pure bosonic states typically achieve Heisenberg scaling.

c. Attaining Heisenberg limit with a single measurement. We prove that pure random bosonic states are typically useful for metrology, even if one is allowed to use *a single* quantum measurement. Concretely, this holds in the natural quantum optics setting of photon-number detection in output modes of a balanced beam-splitter and *for all* values of the parameter.

d. Efficient generation of random symmetric states. Finally, we demonstrate that states generated using short random circuits with gates from a universal gate-set on the symmetric subspace consisting only of beam-splitters and a single non-linear Kerr-like transformation typically also achieve Heisenberg scaling—again even for a fixed measurement. This result shows that the metrological power of random symmetric sates can be be in principle realized experimentally.

As all our findings also equally apply to standard atomic interferometry [4, 5], we hope that our work opens up new possibilities for quantum-enhanced metrology based on random states. Moreover, the metrological usefulness of quantum states is tantamount to the notion of state *macroscopicity* [6], our results directly apply in this context. Finally, since states attaining HL can be used to approximately clone N quantum gates into as many as N^2 gates as $N \to \infty$, one can immediately use our findings to also infer that typical symmetric states provide a resource allowing for optimal *asymptotic replication of unitary gates* [7, 8].

Our work is multidisciplinary as it brings together recent advances in many different fields. On the technical side our results are based on leveraging recent insights concerning the *continuity of quantum Fisher information* [9], *measure concentration techniques* [10, 11], lately proven results about the *spectral gap in the special unitary group* [12], as well as the theory of *approximate t-designs* [13–15].

Our work sheds new light on the role of symmetric states in quantum metrology [16–18]. In particular, it clarifies the usefulness of symmetric states from the typicality perspective [16], but also analytically confirms the findings about their typical properties previously suggested by numerical computations [17, 18].

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Measurement of fractional topological phases with photonic qudits

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Geometrical and topological features play a fundamental role in the realm of quantum theory. Geometric phases were measured by using coincidence detection of photon pairs produced in spontaneous parametric down-conversion (SPDC) in conjunction with a Michelson interferometer, by changing adiabatically the polarization state of the photon pairs, with single photons in a mixed state of polarization by using a Mach-Zenhder interferometer or in a polarization pure state by using a polarimetric technique. The geometric phase on entangled bipartite systems and the role of entanglement in its topological nature have been discussed both theoretically and experimentally for two-qubit systems [1] Later, they were generalized to pairs of qudits of any dimension [2, 3] and to multiple qubits [4], showing that the dimension of the Hilbert space plays a crucial role in determining fractional topological phases in both cases. Experimental schemes for demonstrating these fractional values have been proposed [5, 6].

In this work we present experimental results of fractional topological phase measurements on entangled qudits. Photonic qudits with dimensions $d = 3$ and 4 and qubits (d = 2) were encoded on the transverse positions of quantum correlated photon pairs generated by SPDC. The photon pair is subjected to local unitary operations applied on their spatial degree of freedom using a spatial light modulator (SLM). In order to eliminate any dynamical phase contribution, these operations are restricted to $SU(d)$. For $SU(d)$ transformations the dynamical phase vanishes identically. Fractional topological phases are observed through polarization-controlled two-photon interference. Mukunda and Simon added an important contribution to the understanding of geometric phases[7]. When applied to a pair of d-dimensional entangled systems (qudits A and B), following a cyclic evolution under local unitary operations, their approach allows the derivation of a general formula, $\phi_g = \frac{2n\pi}{d} - \sqrt{C_m^2 - C^2}\,(\Phi_A + \Phi_B) \quad (n \in \mathbb{N})$, where C is the I-concurrence, C_m its maximum value ($C_m = \sqrt{2(d-1)/d}$) and $\Phi_{A(B)}$ is a phase contribution dependent on the whole evolution history of qudit $A(B)$[2, 3]. Our experimental results show clear evidence of the topological phase $2\pi/d$ ($n = 1$) for qudits.

Measurement of the topological phase for qudits is a challenging task. We have to prepare a two-qudit photonic entangled state close to a maximum entangled state; apply a suitable local unitary operation in one of the qudits of the pair and set an interferometer with two possible arms where the two-qudit initial state interferes with the same state transformed by the $SU(d)$ operation. We detect the interference between the entangled two-photon state in path variables and the same state after the application of a local unitary operation to the path degrees of freedom. Fractional topological phases are obtained from the fringe displacement caused by local $SU(d)$ operations applied to the spatial qudits. For different SLM operations the interference pattern shifts and changes the visibility. Fractional topological phases are observed as the phase shifts of the interference fringes when the maximal visibility is recovered. We have tested the discrete phases for two entangled qubits ($d = 2$), qutrits ($d = 3$) and ququarts ($d = 4$) [8]. The experimental two-photon interference patterns confirm that under local $SU(d)$ operations, maximal visibility can only be attained with fractional phase shifts multiples of $2\pi/d$. New measurement strategies of the fractional topological phase will be discussed. This work was supported by CNPq, CAPES, FAPEMIG, National Institute of Science and Technology in Quantum Information, and the Science without Borders Program (Capes and CNPq, Brazil). X.S-L. acknowledges financial support from CONACyT-Mexico.

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Quantum non-Markovianity induced by Anderson localization

Massimo Palma

As discovered by P. W. Anderson, excitations do not propagate freely in a disordered lattice, but, due to destructive interference, they localise. As a consequence, when an atom interacts with a disordered lattice, one indeed observes a non-trivial excitation exchange between atom and lattice. Such non-trivial atomic dynamics will in general be characterised also by a non-trivial quantum information backflow, a clear signature of non-Markovian dynamics. To investigate the above scenario, we consider a quantum emitter, or atom, weakly coupled to a uniform coupled-cavity array (CCA). If initially excited, in the absence of disorder, the emitter undergoes a Markovian spontaneous emission by releasing all its excitation into the CCA (initially in its vacuum state). By introducing static disorder in the CCA the field normal modes become Anderson-localized, giving rise to a non-Markovian atomic dynamics. We show the existence of a functional relationship between a rigorous measure of quantum non-Markovianity and the CCA localization. We furthermore show that the average non-Markovianity of the atomic dynamics is well-described by a phenomenological model in which the atom is coupled, at the same time, to a single mode and to a standard - Markovian - dissipative bath.

Probing the connection between various formulations of macrorealism

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Standard Leggett and Garg inequalities (SLGIs) were formulated for testing incompatibility between the classical world view of macrorealism and quantum mechanics. In recent times, various other formulations, such as, Wigner form of stochastic LGIs (WLGIs), entropic LGIs (ELGIs) and the no-signalling in time (NSIT) condition have also been proposed. In this talk, I first provide a comparative study of the various formulations of LGIs for testing macrorealism for the case of coarse-grained measurements and examine whether classicality emerges by the effect of coarse-graining. Although WLGIs seems to be equivalent to the SLGI but by introducing the notion of operational disturbance I show that the former implies the later but converse does not hold. The role of pair-wise and triple-wise joint measurability in the violation of LGIs will also be discussed.

All-optical quantum simulator of qubit noisy channels

Matteo Paris

We suggest and demonstrate an all-optical quantum simulator for single-qubit noisy channels originating from the interaction with a fluctuating field. The simulator employs the polarization degree of freedom of a single photon, and exploits its spectral components to average over the realizations of the stochastic dynamics. As a proof of principle, we run simulations of dephasing channels driven either by Gaussian (Ornstein-Uhlenbeck) or non-Gaussian (random telegraph) stochastic processes.

Entanglement generation in one-dimensional QED.

Saverio Pascazio

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An excited atom in free space decays towards its ground state through spontaneous emission. Boundary conditions and artificial dimensional reduction can drastically modify this picture, enhancing or inhibiting (and sometimes essentially hindering) decay.
We investigate the behavior of two quantum emitters embedded in a linear waveguide, in a quasi-one-dimensional configuration. We find that they can relax towards bound states for resonant values of the interatomic distance. The stability of such states is studied, and their relevance for entanglement generation is analyzed.

Internal dynamics of intense twin beams and their coherence

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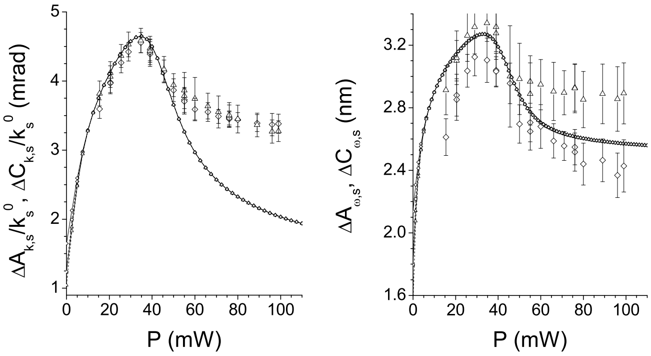
The dynamics of intense twin beams in pump-depleted parametric down-conversion [1] is studied using the spatio-spectral Schmidt modes [2]. A generalized parametric approximation is suggested to solve the quantum model [3]. Its comparison with a semiclassical model valid for larger twin-beam intensities confirms its applicability [4]. The experimentally observed maxima in the spectral and spatial intensity auto- and cross-correlation functions depending on pump power are explained in terms of different speeds of the (back-)flow of energy between the individual down-converted modes and the corresponding pump modes (see Fig. 1). This effect is also responsible for the gradual replacement of the initial exponential growth of the down-converted fields by the linear one. Furthermore, it forms a minimum in the curve giving the effective number of twin-beam modes. These effects manifest a tight relation between the twin-beam coherence and its internal structure, as clearly visible in the model. Multiple maxima in the intensity correlation functions originating in the oscillations of energy flow between the pump and down-converted modes are theoretically predicted.

As indicated by a theoretical model, depletion of the pump beam may also result in the generation of coherent components in the signal and idler fields that weaken the ideal pairing of photons in the twin beam [5].



(a) (b)

FIG. 1: (a) Spatial radial and (b) spectral widths ΔA_s and ΔC_s of intensity auto- ($\diamond$, black) and cross-correlation ($\triangle$, red) functions, respectively, versus pump power P; experiment (isolated symbols with error bars [1]), generalized parametric approximation (solid curves with symbols), semiclassical model (dashed curves with symbols); $A_s(x,x') \equiv \langle \Delta[\hat{a}_s^\dagger(x)\hat{a}_s(x)]\Delta[\hat{a}_s^\dagger(x')\hat{a}_s(x')]\rangle_{\mathcal{N}}$, $C_s(x,x') \equiv \langle \Delta[\hat{a}_s^\dagger(x)\hat{a}_s(x)]\Delta[\hat{a}_i^\dagger(x')\hat{a}_i(x')]\rangle_{\mathcal{N}}$, $\hat{a}_b(x) \equiv \hat{a}_b(k_b^\perp,\varphi_b,\omega_b) = \sum_{mlq} t_{b,ml}^*(k_b^\perp,\varphi_b) f_{b,q}^*(\omega_b)\hat{a}_{b,mlq}$ and $t_{b,ml}$ ($f_{b,q}$) are the spatial (spectral) Schmidt modes of field b, $b=s,i$. For more details, see [2]. All 4 curves in (a) and (b) nearly coincide.

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Internal dynamics of intense twin beams and their coherence

Jan Peřina Jr.,[1,*] O. Haderka,[1] A. Allevi,[2] and M. Bondani[3]

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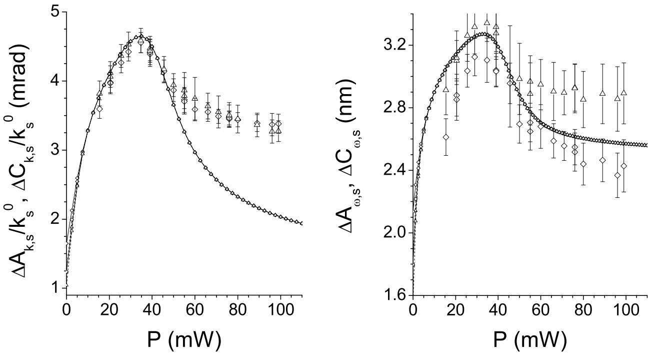

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Open Quantum Brownian motion: Gaussian and non-Gaussian behaviour

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Open Quantum Brownian Motion (OQBM) describes a Brownian particle with an additional internal quantum degree of freedom. Originally, it was introduced as a scaling limit of Open Quantum Walks (OQWs). Recently, it was noted, that for the model of free OQBM with a two-level system as an internal degree of freedom and decoherent coupling to a dissipative environment, one could use weak external driving of the internal degree of freedom to manipulate the steady-state position of the walker [Sinayskiy, I., and Petruccione, F. (2016). Fortschr. Phys.. doi:10.1002/prop.201600063]. This observation establishes a useful connection between controllable parameters of the OQBM, e.g. driving strengths and magnitude of detuning, and its steady state properties. Although OQWs satisfy a central limit theorem (CLT), it is known, that OQBM, in general, does not. The aim of this work is to derive steady states for some particular OQBMs and observe possible transitions from Gaussian to non-Gaussian behavior depending on the choice of quantum coin and as a function of diffusion coefficient and dissipation strength.

Quantum information and quantum metrology with continuous variables

Olivier Pfister

Continuous quantum variables are epitomized by the position and momentum quantum operators, which find easy physical implementation in the laboratory in the context of quantum harmonic oscillators. Quantum optics in resonators, in particular, yields well defined quantum eigenmodes which can be efficiently coupled with parametric nonlinear interactions such as in optical parametric oscillators (OPO). In this talk, we will present our use continuous-variable squeezed states to produce massively scalable cluster entangled states, suitable with universal quantum computing, in a single OPO. We will also expound on the effective interplay of wave-particle duality with exponential speedup, quantum error correction, and quantum metrology.

Genetic Quantum Measurement

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Measurements are the very basis of Physics, especially in Quantum Mechanics, where they assume even a more fundamental role. Apart from usual projective measurements, causing the wave function collapse into an eigenstate of the measured operator, in Quantum Mechanics other kinds of measurement are possible, some of them featuring several interesting properties.

An example of these are Weak Measurements [1-3], realised for the first time in [4-6] and used for addressing fundamental questions [7-12] as well as a very promising tool for Quantum Metrology [13-19].

One of the most intriguing properties of Weak Measurements is that, since they rarely lead to wave function collapse, they can allow gathering simultaneous information on non-commuting observables [20,21], impossible with the standard (projective) measurement protocols.

A second example is provided by Protective Measurements [22,23], a new technique able to extract information regarding the expectation value of an observable even by measuring a single (protected) particle.

Here we present a novel quantum measurement protocol called Genetic Quantum Measurement, exploiting a genetic-like approach to measurement that mimics the evolution-inspired processes of mutation, crossover and selection, typical of genetic algorithms in computer science [24]. This protocol can be also seen as a special kind of quantum random walk [25].

Genetic Quantum Measurements are composed of a sequence of steps consisting of an interaction-interference part followed by a selective (i.e. projective) measurement. Interaction-interference essentially couples the observable of interest to a pointer observable, whose measurement provides indirect estimation of the observable of interest. For a reasonable number of interactions and for specific interaction strength, this protocol outperforms, in terms of uncertainty reduction, the conventional projector-based quantum measurements (even when they represent the optimal measurement, i.e. the one saturating the quantum Cramer-Rao bound). This technique also overcomes more advanced methods in terms of practicality. For these reasons, the Genetic Quantum Measurement approach appears to be an intriguing technique that may have far-reaching implications on the area of quantum measurement, therefore being of the utmost interest for all the quantum technologies and, in particular, for quantum metrology and quantum-enhanced measurement.

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Remote polarization entanglement generation by local dephasing and frequency upconversion

Jyrki Piilo

Photons have recently been used to simulate open system dynamics and to control non-Markovian memory effects in their dynamics [1,2]. This has also allowed the realization of non-local memory effects [3-4] and their exploitation is superdense coding [5]. In the current work we exploit initial frequency entanglement between the photons and show theoretically how this can be converted to their polarization entanglement by local processes only. This opens the possibility, e.g., to prepare polarization entanglement remotely by using local dephasing processes. Time allowing, we also discuss how the control of initial polarization-frequency correlations allows to construct generic quantum simulator for dephasing.

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Full Characterization of Single-Photon States in a Single Measurement

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Single-photon sources are characterized by the normalized second-order correlation function and indistinguishability. The second-order auto-correlation function characterizes the photon statistics and is related to measurements by Hanbury Brown and Twiss (HBT), denoted $g^{(2)}_{\mathrm{HBT}}$. The second-order interference of the two input fields can be measured via a similar correlation function, referred to as Hong, Ou, and Mandel (HOM) interferometry. The significance of the HOM measurement is that it determines indistinguishability C of the interfering non-entangled input states. Typically, any realistic measurement of C requires at least one supplemental measurement to determine $g^{(2)}_{\mathrm{HBT}}$.

Here we show a method to simultaneously access the single photon purity and indistinguishably. This measurement relies on either a photon-number resolving detector or a primitive boson sampler. The two replicas of the state under measurement are sent to a first beamsplitter. Each of the outputs of the first beamsplitter is subsequently sent onto a photon-number resolving detector or a beamsplitter cascade. The statistics of light that exits this photonic circuit is defined by both $g^{(2)}_{\mathrm{HBT}}$ and C. In characterizing Fisher information, we prove that our method provides more knowledge about the input state than a conventional method using the same quantum resource. To demonstrate the new method, we characterized light from a single quantum dot. We compare this new approach with a traditional HBT measurement. We also compare the HOM visibilities, one calculated from the data obtained with our method and the other directly obtained through a traditional experiment. The measurements compare well.

To conclude, we theoretically introduce and experimentally demonstrate a new measurement method to simultaneously characterize a state of light by taking advantage of boson sampling.

Interaction and Entanglement of Few-Photon Quantum Light with Atoms

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The interaction of quantum electromagnetic field with matter is a very interesting and important problem of modern quantum physics. Today the experimental generation of non-classical states of light becomes possible. Among them few-photon Fock and coherent states with small mean photon number, biphoton pairs and multiphoton squeezed states of light [1-3]. This fact strongly stimulates theoretical investigations of interaction of such quantum fields with atomic and molecular systems. To take into account an additional field degree of freedom seems to be a rather difficult theoretical problem. At the same time the possible entanglement between atomic and field subsystems leads to many new and important phenomena and applications. One of the most promising applications concerns the quantum information and quantum computing purposes. The most important problem in this case is to provide a coherent control of atomic system. This can be performed using a superposition of photon states with some relative phases between them. As one of the simple example of such state the few-photon coherent state can be chosen. The influence of the field phase and the role of the phase uncertainty is an important and scantily explored problem.

We consider an interaction of three-level atom with two resonant electromagnetic quantum fields in lambda-configuration. Both fields are supposed to be coherent states with small mean number of photons which can be much less than 1. Under these conditions the phases of used coherent states are not exactly determined values and are characterized by same uncertainty. The dynamics of atomic system is investigated analytically in dependence on the relative phase between the two fields and for different phase uncertainties. The entanglement between the atomic and field subsystems is analyzed. The evolution of the photon statistics of the fields during the interaction is examined. The possibility of formation of the “dark” atomic state and coherent population trapping [4] is proved in dependence on parameters of the coherent states applied. The way to determine the relative phase from the atomic state formed during the interaction is discussed.

In addition the obtained results are compared to atomic evolution in the case of the two classical fields applied. If these fields are exactly resonant and have the same envelopes, the problem has an analytical solution. Otherwise we obtained the solution numerically for the wide range of parameters.

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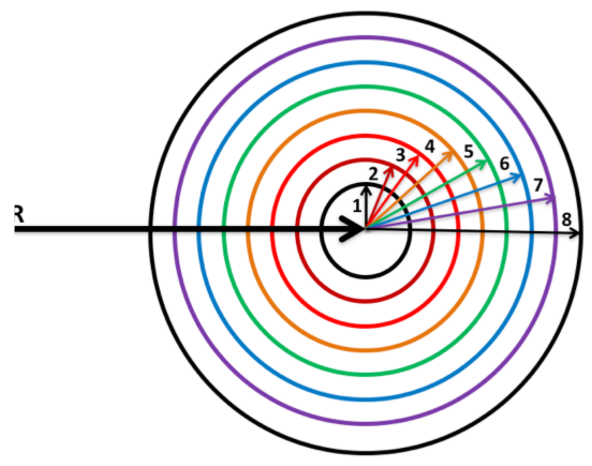
ANALYTICS OF QUANTUM PHYSICS OR QUANTUM LANGUAGE OF UNIVERSE



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Abstract

Gauss attempt to develop absolute metric system was unsuccessful because of the Inconsistency of Hyperbolic and Elliptic geometry.

Parabolic and Logarithmical bonds of numbers PI and E avoid this inconsistency and completely coordinate the values of Quantum Constants.

Analytic expressions for Speed of light, Kelvin, Molar mass, Boltzmann, Avogadro, Planck, Fine structure, Elementary Charge, Background Temperature and Gravitation constants are derived and can be calculated with practically unlimited accuracy 1/10^64.

Metric base for New SI-2018 is created without use of artifacts (m, s, kg) and measurements at all.

A way to Quantum computing is open.

CONSTANT	CODATA-2014	EXACT ANALYTICAL
Speed of light	299792458(conventional)	299792457.86759134
Background temperature	2.725(not valued)	2.7252543275634558
Relative molar mass	0.012(conventional)	0.0119992777505492
Kelvin	2.7316(conventional)	2.7315999984590452
Fine structure	0.0072973525664(17)	0.0072973525205056
Avogadro	6.022140857(74)	0.006022141056*10^26
Boltzmann	1.38064857(74)	1.380648450231*10^-23
Planck	6.626070040(81)	6.626070011116*10^-34
Elementary charge	1.6021766208(98)	1.602176615025*10^-19
Gravitation	6.67408(31)	6.674052911255*10^-11

Quantum Physics is Absolute Metric System
Quantum Physics is Complex Differential Geometry
Quantum Constants are Dynamic Eccentricity Differential Units
Quantum Constants are Polar Geometrical Parameters of 3D Wave front motion
Quantum Constants are Dynamic Gradients of Log-Normal Distribution
Quantum Physics is Noncommutative Discrete Mathematics
Quantum Physics is Universal Calculus

Continuous Math	E^(j*PI) +1 = 0	Euler
Quantum Math	E^(j*PI) +1 = [A]/10^57	Electron Alpha-Matrix
Discrete Math	E^(j*PI) +1 = 1/10^64	Gauss

ELECTRO AND THERMODYNAMICS

C = (R +4*PI*C/10^18) ^ 64*10^7 = 299792457.867591338433684,
R = Integer[10^8*(C/10^7) ^ (1/64)]/10^8 = 1.05456978.

C is the Rotational speed of radius-vector in the 3D space. R is the length of the corresponding inverse squared radius. 4*PI is the Solid angle in radians. The value 4*PI*10^-7 is the Magnetic constant. The value 4*PI*C*10^-7 is the Impedance of free space. The value 1/(4*PI*10^-7)/C^2 is the lower limit of Electric constant.

Number C is the Speed of light in physics, but arithmetically it is a quantity of turns around a ball with the radius 4*PI/10^18 during a unit of time.

K = E +AS +BS = 2.7315999984590452.
AS=1/Sum{[137+{137-100)*n]/10^(3*n)=1/100/(1.1111111111111111…)^3=0.00729000000000000000000...
BS=Sum[602214183/10^(3*n+11)]=0.0060281699999999999999…397183=0.0060281699999999999999…

K (kelvin) is upper limit of inverse tempo-rate. “Temperature” literally means “rating of tempo” or “rating of rapidity of vibrations”. Value of translational velocity oscillates between the values of rotational and vibrational speeds. Number E is lower limit of inverse tempo-rate.

Numbers AS and BS link “two letters alphabet” (0...1) and “ten letters alphabet” (0...9) because 1= (0.999999...) and 10 = (9.99999...). Number 137 links binary and decimal calculus. Number B = 602214183 is Avogadro integer.

APPROXIMATE GAUGE EQUATIONS

[sqrt((PI^2+E^2)/2) + (PI+E)/2 + sqrt(PI*E) + sqrt(PI*E) + 2*PI*E/(PI+E)] ^2 = 137
E^137 = 100*PI*(10^57) = 100*sqrt(10)*(10*57)
1+sqrt(2*PI*E/100) = sqrt (2)

BASIC EQUATIONS OF QUANTUM CALCULUS

[G]= 2*PI*[R]*(1+[A]) = [P]*(1+[A])

[R] is Planck-Dirac relative radius matrix
[P] is Planck relative perimeter matrix
[Ri] = 1+2/100*(E+[Ai]*(1+sqrt(2*PI*E/100)))
[A] is Sommerfeld-Born relative eccentricity matrix
[G] is Newton wave fronts space density matrix
[Ai] = (([Ri]-1)*100/2-E)/(1+sqrt(2*PI*E/100))

Sqrt(2*PI*E) is Gauss Parameter of Information Entropy of Normal Distribution

ORBITAL ATOM PARAMETERS

A4 = (PI*E/100)+4*{1/137-(PI*E/100)^2}	R4 = 1.0545725104198716
AL = 1/{1+59*ln(10)}	RL = 1.0545721761536017
A1 = 1/137	R1 = 1.0545719538152265
AF = 1000/Integer{1000*sqrt(137^2)}	RF = 1.0545718996147182
A0 = (PI*E/100)^2	R0 = 1.0545717682803448
AS = 1/Sum{[137-(137-100)*n]/10^(3*n)}	RS = 1.0545716917923240

10^0/10^2/(10^0+10^-1+10^-2+10^-3+…)^3 = AS is Atomic Symmetry Center AS = 3^6/10^5

NUCLEAR ATOM PARAMETERS

AS = 1/100/(1.11111111111…)^3	RS = 1.0545716917923240
AC = 0.0072224962396475	RC = R+4*PI*C/10^18
AE = 0.0072224931083101	RE = R+1/E/10^8
AA = 0.0072224927601997	RA = R+1/(E+AS)/10^8
AK = 0.0072224924737441	RK = R+1/(E+AS+BS)/10^8
AX = 5/X-1	RX = 1.0545642346951568
X = Root(X*E^X/(E^X-1))	

“EXACT” GAUGE EQUATIONS

P1-P0 = {4*PI*(10^-7)}*{2*E/(PI+E) - cos(PI/6)*(10^-4) – tan(PI/4)*(10^-7) + sin(PI/6)*(10^-9)}
E = 2.7182818284590452 = (137/100)*(12/10)*{16534561/10^7+(360-1)/10^13}+2^8/10^16
PI = 3.1415926535897932 = (314159265359/10^11)-4*517/10^16

SEVEN BASIC GAUGE DIGITAL SEQUENCES

PI = Sum from (-1) to (+1) of {d(1/N)/sqrt[1-(1/N)^2]} where N tends to Infinity.
PI = 31415926535897932/10^16 is Absolute Space Number (perimeter of circle with diameter 1).

E = (1+1/N)^N where N tends to Infinity.
E = 27182818284590452/10^16 is Absolute Time Number (base of natural logarithm).

C = (R+4*PI*C/10^18)^64*10^7
C = 299792457.8675913384336840/10^16 is Harmonic Rotational Speed Unit (Maxwell number).

R = Integer of [(C/10^7)^(1/64)*10^8]/10^8
R = 1.05456978 is Harmonic Inverse Squared Radius (Dirac number).

K = E+AS+BS
K = 27315999984590452/10^16 is Upper Limit of Inverse Temperature (Kelvin number)

AS = 1/Sum of {[137+(137-10^2)*N]/[10^(3*N)] where N moves from Zero to Infinity = 729/10^5
AS = 1/(10^2)/(1.1111111111111111111111111111111111111111111111111…)^3 = 729/10^5
AS = (10^0)/(10^2)/ [(10^0)+(10^-1)+(10^-2)+(10^-3)+(10^-4)+(10^-5)+(10^-6)+...]^3 = 729/10^5
AS = 9^3/10^5 = 3^6/10^5 = 3^6/2^5/5^5 = 3*3*3*3*3*3/(2*2*2*2*2)/(5*5*5*5*5) = 729/10^5
AS = 0.00729 is Mirror Symmetry Unit (11111111111111111111> is Schrodinger Qubit number)

BS = Sum of {[602214183/[10^(11+3*N]} where N moves from Zero to Infinity = 602817/10^8
BS = 0.00602816999999999999999999999999999999999999999…397183 = 602817/10^8
BS = 0.00602817 is Information Entropy Reference Unit (B = 602214183 is Avogadro integer).

HARMONIC PROGRESSIVE VELOCITY

(R+4*PI*C/10^18)^64/10 = CH = 2.9979245786759074*10^8 (upper limit of V)
Median of (T…CH) = 2.9979245697688564*10^8 = V (harmonic translation velocity)
T = 2.9979245608618054*10^8 (lower limit of V)

HARMONIC ORBITAL RADIUS

RF = 1.054571899615 (fine structure radius)
Median of (RP…RF) = 1.054571847578 = RQ (harmonic orbital relative inverse radius)
RP = 1.054571795542 (orbital Planck radius)

ELEMENTARY CHARGE UNIT

QT = sqrt(1000*AF*RP/T) = 1.602176617405 (upper limit of Q)
Median of (QC…QT) = 1.602176615025 = Q (elementary charge unit)
QC = sqrt(1000*AF*RP/CH) = 1.602176612620 (lower limit of Q)

HARMONIC NUCLEAR RADIUS

RS = 1.054571691792
Median of (RV…RS) = RVS
RV = 1.054569783718
Median of (RVX…RVS) = RM = 1.054568873479
Median of (RV…RX)= RVX
RX = 1.054564234695

FINE STRUCTURE UNITS

Eccentricity AF = 1000/Integer{1000*sqrt(137^2+PI^2)} = 0.0072973525205056
Radius RF = 1+2/100*{E+AF*[1+sqrt(2*PI*E/100)]} = 1.0545718996147182

HARMONIC PLANCK UNIT

P1 = 6.6260710055755006
P01 = 6.6260704227004664 (Median of P0…P1)
PP = 6.6260700111158525 = Planck perimeter unit (Median of medians)
P0 = 6.6260698398254579
P0S = 6.6260696995312512 (Median of P0…PS)
PS = 6.6260693592370495

HARMONIC BACKGROUND TEMPERATURE

(E+AS+BS) = 2.731599998459
Median of (A…K) = 2.728585081095 = TBU (upper limit of “relic” tempo-rate)
E+AS = 2.725571828459
Median of medians = 2.725254327563 = TBG (harmonic background or “relic” tempo-rate)
Median of (A…E) = 2.721925608181 = TBL (lower limit of “relic” tempo-rate)
E = 2.718281828459

HARMONIC NUCLEAR TEMPERATURE

TE = (R+1/E/10^8)^64*10^7 = 299792456.25727398
Median of (TA…TE) = TU (upper limit of T)
Median of medians = 299792456.08618054 = T (harmonic nuclear tempo-rate)
TA = (R+1/(E+AS)/10^8)^64*10^7 = 299792456.07825528
Median of (TA…TK) = TL (lower limit of T)
TK = (R+1/(E+AS+BS)/10^8)^64*10^7 = 299792455.93094307

HARMONIC RELATIVE MOLAR MASS

MM = {12-[AT…AC]/10}/1000 = 0.0119992777505492

HARMONIC BOLTZMANN UNIT

KB = cos{12-[AT…AC]/10}-sin{12-[AT…AC]/10} = 1.380648450231

HARMONIC AVOGADRO UNIT

NA = {sqrt{8*PI*E/(8*PI*E+137^2)}/[1+2*(A4...AL)/1000]-5/10^8}/10 = 0.006022141056

HARNONIC GRAVITATIONAL UNIT

The value of Newtonian gravitational constant G is identified as the value of harmonic density of the velocity field:
2*PI*RQ*(1+AQ) = 6.6744109106473266 = GQ.
Median (GM; GQ) = 6.6740529010349328 = G. CODATA value is 6.67408(31).
2*PI*RM*(1+AM) = 6.6736948926580828 = GM.

COMPLEX VERIFICATION

The following below shows that an excellent complex verification of a mutual coordination of quantum units:
Molar gas constant (thermodynamics): KB*NA = 8.3144597407083043. CODATA value is 8.3144598(48).
Wien wavelength displacement (quantum physics): 2*PI*RP*V/KB/X = 0.028977730384396. CODATA value is 0.028977729(17).

DECIMAL ORDERS OF QUANTUM CONSTANTS

Decimal orders of quantum constants are determined from the equations of the standard physical model using an approximate exponential expression E^137 = 100*PI*10^57. For KB this value is 10^-23. For NA it is 10^+23.
For RP and PP the decimal order is 10 ^-(57-23) = 10^-34. For Q it is 10^-(8+11) = 10^-19 and for G it results in 10^+(8-19) = 10^-11.

PHYSICS IS QUANTUM LANGUAGE OF UNIVERSE

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Applications of Optomechanical Quantum Correlations

Tom Purdy

Cavity optomechanical systems can produce a strong, effective, Kerr-like optical nonlinearity. Applications relying on this nonlinearity include the generation of quadrature squeezed light, quantum-efficient frequency conversion of signals between optical and microwave bands, and potentially obtaining measurement sensitivity below standard quantum limits for systems ranging from nanoscale force microscopy to gravitational wave detection.

We employ optomechanics for quantum temperature metrology.We optically detect the Brownian motion of a nanomechanical resonator to measure its temperature.

Because it is often difficult to accurately calibrate such optical signals, we additionally measure the scale of the mechanically induced, optical quantum correlations in our probe light, and use this scale to calibrate the size of the thermal motion.

Correlations between optical quadratures of the probe arise when the optical force from shot noise intensity fluctuations of the probe light drives mechanical motion that is written back onto the phase of probe light (along with the uncorrelated thermal motion).

The optical force noise constitutes the quantum backaction of our displacement measurement, and so the size of the quantum correlations is fundamentally set by a Heisenberg measurement-disturbance uncertainty relation.

This work demonstrates a path towards absolute thermometry with quantum mechanically calibrated ticks and gives a first glimpse at quantum measurement processes in a room temperature nanomechanical system.

QUANTUM 2017 - 8th Workshop ad memoriam of Carlo Novero
7-13 May 2017, Università di Torino, Italy

EXACT SPECTRUM OF THE MULTI-PHOTON JAYNES-CUMMINGS MODEL

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We utilize the unitary transformation method for the closed form solution of the multi-photon Jaynes-Cummings (JC) model. In particular, we establish the unitary transformation, which leads to the diagonalization of the relevant Hamiltonian. We also show that there is a correspondence between the JC and the anti-Jaynes-Cummings (AJC) models: this latter result enlightens the connection between JC and AJC interactions and the physical systems of the cavity quantum electrodynamics and laser-driven trapped ions.[1]

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Diamond photonics and NV centers enabled by femtosecond laser writing

Shane M. Eaton, Roberta Ramponi

Diamond's nitrogen vacancy (NV) center, which is present in both naturally occurring and synthetically fabricated diamond, consists of a nitrogen with a neighboring empty site replacing carbon atoms in the diamond lattice. The optically active defect boasts long room temperature spin coherence time, making them attractive as quantum bits [1]. In addition, due to the magnetically sensitive ground state of NV centers, they can be used to measure weak magnetic fields with nanoscale resolution, which has triggered significant research into diamond-based optical magnetometers [2]. An integrated optics platform in diamond would be beneficial for magnetometry due to the enhanced interaction provided by waveguides, and quantum computing, in which NV centers could be optically linked together for long-range quantum entanglement, due to stability and integration provided by monolithic waveguides. However, it remains a challenge to fabricate optical waveguides in diamond, particularly in 3D, due to its hardness and chemical inertness.

We recently demonstrated the fabrication of 3D optical waveguides in bulk diamond using focused ultrashort laser pulses [3]. As confirmed by optically detected magnetic resonance and μRaman spectroscopy, we showed that the high repetition rate laser writing produced a waveguide with preserved crystallinity.

The concentration of NV centers depends on the purity of the diamond, however the defects are randomly distributed throughout the volume. It is highly desirable to deterministically produce NVs on demand with submicron resolution, prealigned with existing photonic circuits. Recently, Chen *et al.* demonstrated that femtosecond laser exposures produced vacancies in bulk diamond. After annealing at 1000°C, the laser formed vacancies diffused toward nitrogen impurities to produce on-demand and high quality single NVs [4].

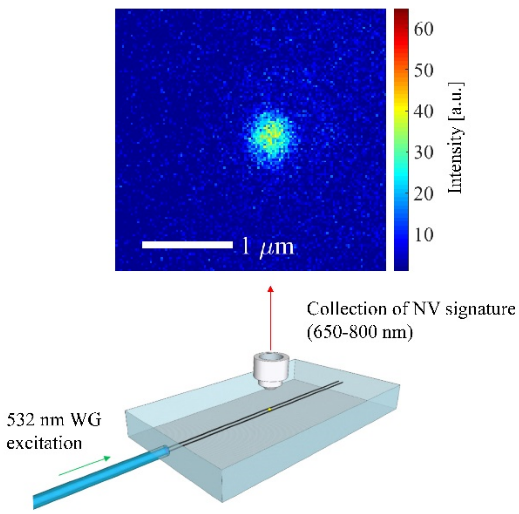

Figure 1. Below: 532-nm wavelength excitation of single NV center using optical waveguide. Above: NV signature is captured using EMCCD imaging.

We have taken these pioneering works of laser fabrication of optical waveguides [3, 5] and NVs [4] a step further, by incorporating these important building blocks on the same integrated diamond chip, to enable the robust excitation and collection of light at NVs [6]. Using wide-field EMCCD imaging, we demonstrated the coupling of single NVs using optical waveguides (Figure 1).

Optically addressed NV centers could open the door for more sophisticated quantum photonic networks in diamond. For example, in quantum grade diamond, the optically linked single NVs could be exploited for single photon sources or solid state qubits. In lower purity diamond, the laser writing of high density NV ensembles within waveguides could enable robust excitation and collection of the fluorescence signal for magnetometry.

Acknowledgments

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Einstein-Podolsky-Rosen-Bohm Gedankenexperiment with classical light waves

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Abstract

I show that the Einstein-Podolsky-Rosen-Bohm Gedankenexperiment and so-called entanglement of photons have a simple explanation within the framework of classical electrodynamics if we take into account the discrete (atomic) structure of the detectors and a specific nature of the light–atom interaction. In this case we do not find such a paradox as "spooky action at a distance". I show that CHSH criterion in EPRB Gedankenexperiment with classical light waves can exceed not only a maximum value $S_{HV}=2$ which is predicted by the local hidden-variable theories but also the maximum value $S_{QM}=2\sqrt{2}$ which is predicted by quantum mechanics and in this case there is no desire to construct a local hidden-variable theory.

Experimental Realisation of Protective measurements

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In this communication we present the first experimental realisation of Protective Measurements [1], The polarisation of a heralded single photon has been weakly coupled through birefringens to the momentum of the pointer. The protection of the quantum state is realised by Zeno effect through a polarisation projecton. After having repeated the operation 7 times the position of the incoming photon (pointer variable) has been measured by a prototype ccd camera. The achieved values of the protected measure perfectly agree with what expected from the theory, demonstrating that a single-event detection can provide reliable information regarding a certain property of a quantum system -the expectation value of the polarisation operator- supposed to be only statistical, belonging to an ensemble of identically prepared quantum systems. In doing this, PMs require that prior information on the preparation stage is exploited in realising the protection.
Our result paves the way to application to quantum technologies, as testing state preparation.

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Light-matter quantum interferometry with homodyne detection

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The rapid development of quantum technology crucially depends on the quality of quantum metrology of matter systems. Due to recent progress in the field, optical interferometry using light as a probe modified in the optical phase by a matter sample [1] can be combined with quantum interfaces and transducers between matter and light or microwaves [2]. This allows a use of matter at quantum level as a new sensitive probe of physical processes caused by its environment, as was recently pioneered in quantum magnetometry.

In our work, we investigated the estimation of an unknown Gaussian process (containing displacement, squeezing and phase-shift) applied to a mechanical system. The state of the mechanical system cannot be directly measured, instead, we measure an optical mode which interacts with the system. We propose an interferometric setup exploiting a beam-splitter-type of the light-matter interaction with homodyne detectors and two methods of estimation. These are based separately either on the means or on the covariance matrix of the measured optical amplitudes. We compare the interferometry to two non-interferometric estimation methods (using only the thermal noise of matter and using a mixture of thermal noise and coherent light without interferometry) and show that the best accuracy of estimation is achieved with the interferometric setup. Importantly, we show that even limited coupling strength [3] is sufficient for very good estimation. We demonstrate that, generally, by having a stronger source of coherent light a more noisy mechanical system can be tolerated. The results suggest that the proposed light-matter interferometry is feasible in realistic settings, thus, it can open the way for future investigations of specific experimental platforms in quantum metrology of matter systems.

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Quantifying nonclassicality by characteristic functions

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In quantum optics, many concepts have been developed to, on the one hand, distinguish classical from nonclassical states of light and, on the other hand, quantify their nonclassicality. An established definition of a nonclassical radiation field is given in terms of the Glauber-Sudarshan P function,[1]which results in an expansion in terms of classical coherent states. If the phase-space distribution P fails to be interpreted in terms of classical probability theory, the corresponding state is nonclassical.[2] This definition allows for formulating many, complementary nonclassicality measures. For example, one approach is adding classical noise to the state until its P function becomes classical. The resulting amount of noise is used to quantify the nonclassicality.[3] Our nonclassicality measure is directly based on the fundamental quantum superposition principle. Namely, the minimal number of superpositions of coherent states which are required to describe the state under study defines the degree of nonclassicality.[4]

In the present contribution, we formulate several ways to determine or estimate the degree of nonclassicality by studying the properties of the characteristic functions, the Fourier transform of the Glauber-Sudarshan P functions.[5] Because of the singular behavior of the P function for many quantum states, we study the well-behaved characteristic function, which can be sampled by balanced homodyne detection. For states with finite Fock expansions, a one-to-one relation is derived between the polynomial order of the characteristic function and the degree of nonclassicality. Additionally, the influence of quantum processes, i.e., photon addition and subtraction, on the amount of nonclassicality is elaborated. For states with an infinite polynomial order, the degree of nonclassicality can be lower bounded—assuring a minimal amount of quantumness. For this reason, we generalize the nonclassicality criterion for the absolute value of the characteristic function,[6] to be applicable for our quantification. The resulting sufficient conditions are consistent and, for some examples, even exceed the range of applicability compared to earlier techniques.[7] In particular, we compare two different ways of combining a nonclassical squeezed and a classical vacuum state: their quantum superposition and their classical mixture. The impact on the verifiable degree of nonclassicality of the resulting state is analyzed with our method.

In summary, we provide criteria to access the amount of nonclassicality of quantum light. Our approach is based on the measurable characteristic function. For states with finite number-state expansion, our criteria are necessary and sufficient and for general states, they are sufficient.

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Achieving sub-shot-noise absorption-spectroscopy with avalanche photodiodes and with a charge-coupled device

Javier Sabines

Chemical and biological samples can be interrogated by measuring the spectral absorption of light. When low intensity is used to illuminate a sample, the signal-to-noise ratio of absorption features is limited fundamentally by the quantum nature of light. When an intensity measurement is performed on the coherent state we obtain a probabilistic measurement outcome for the intensity with a Poisson distribution. This is the shot noise limit and this uncertainty impacts on estimates of physical properties that are derived from an optical measurement. There are scenarios where it is advantageous to maximize the precision achieved whilst minimizing the intensity of the input probe. It has been shown that Fock states can enable precision in absorption estimation beyond the shot noise limit and that Fock states are the optimal quantum state for maximizing precision. In the present work we use correlated photon pairs to achieve sub-shot-noise absorption spectroscopy. The experiment uses a type II phase matched PPKTP crystal pumped by 404nm light to generate separable pairs of photons. We adjust the crystal temperature to tune the wavelength of a probe photon beam through the absorption features of a sample using the other beam either as a herald or reference. We use this setup to demonstrate evidence for sub-shot-noise performance towards the ultimate quantum limit using three forms of measurement: (i) We incorporate an optical delay and switch into the previous scheme. This feed forward scheme yields sub-shot-noise performance per photon flux and we observe an advantage of up to 27.5 ± 8%; (ii) In our latest work we direct the two orthogonally polarized output channels of the source onto two separate pixel regions of a cooled, high efficiency, commercial CCD camera. Here we observe sub-shot-noise performance with a mean normalized variance of the detected intensity difference between the two beams of 0.40 ± 0.01.

Quantum detection and quantum simulation of traversable wormholes

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ORAL PRESENTATION

Traversable wormholes are compelling mathematical objects appearing in some solutions of Einstein's General Relativity equations. Since they provide a bridge between distant regions of spacetime, they have attracted a great deal of attention from a foundational viewpoint as well as at a pedagogical level. They might contain closed timelike curves (CTCs), which are also interesting for Quantum Computing applications, since they would boost the capabilities of quantum computers. Moreover, since wormholes can be â€œblack hole mimickersâ€, the source of several phenomena commonly attributed to black holes might be questioned, including the gravitational waves recently observed by advanced LIGO.

In this talk, I show that wormholes are, in principle, detectable with similar ideas and technology as the ones successfully employed in gravitational wave astronomy.A coherent state of the electromagnetic field experiences a phase shift with a slight dependence on the throat radius of a possible distant wormhole. I show that this tiny correction is, in principle, detectable by homodyne measurements after long propagation lengths for a wide range of throat radii and distances to the wormhole, even if the detection takes place very far away from the throat, where the spacetime is very close to a flat geometry. I use realistic parameters from state-of-the-art long-baseline laser interferometry, both Earth-based and space-borne. The scheme is, in principle, robust to optical losses and initial mixedness.
Moreover, I present an analog quantum simulator of spacetimes containing traversable wormholes. A suitable spatial dependence in the external bias of a dc-SQUID array mimics the propagation of light in a 1D wormhole background. The impedance of the array places severe limitations on the type of spacetime that we can implement. However, we find that wormhole throat radius in the sub-mm range are achievable. We show how to modify this spacetime in order to allow the presence of closed timelike curves. The quantum fluctuations of the phase due to the impedance might be seen as an analogue of Hawking's chronology protection mechanism. This quantum simulator could be a useful low-cost Earth-based source of information for an actual experimental test of traversable wormhole detection.

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Quantum metrology at the limit with extremal Majorana constellations

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ABSTRACT

Quantum metrology allows for a tremendous boost in the accuracy of measurement of diverse physical parameters. The estimation of a rotation constitutes a remarkable example of this quantum-enhanced precision. When the rotation axis is known, NOON states are optimal for this task, achieving a Heisenberg-limit scaling. On the other hand, when the axis is unknown, we show that the optimal states are the recently introduced Kings of Quantumness. We consider the problem in terms of the Majorana stellar representation. The Majorana constellation of NOON states consists of points equidistantly placed around the equator of the Bloch sphere, whereas for the Kings it consists of points uniformly distributed over the sphere. Here, we report the experimental realization of these states by generating up to 21-dimensional orbital angular momentum states of single photons, and confirm their superior sensitivity for measuring a rotation about an arbitrary axis.

Experimental violation of local causality in a quantum network

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Abstract: Using a photonic setup we investigate a quantum network consisting of three spatially separated nodes whose correlations are mediated by two independent sources. This scenario allows for the emergence of a new kind of non-local correlations that we experimentally witness by violating a novel Bell inequality. Our results provide the first experimental proof-of-principle of generalizations of Bell's theorem for networks, a topic that has attracted growing attention and promises a novel route for quantum communication protocols.

Non-locality stands nowadays not only as one of the cornerstones of quantum theory, but also plays a crucial role in quantum information processing. Several experimental investigations of nonlocality have been carried out over the years. In spite of their fundamental relevance, however, all previous experiments do not consider a crucial ingredient that is ubiquitous in quantum networks: the fact that correlations between distant parties are mediated by several, typically independent, sources of quantum states. Here, using a photonic setup we investigate a quantum network consisting of three spatially separated nodes whose correlations are mediated by two independent sources. This scenario allows for the emergence of a new kind of non-local correlations that we experimentally witness by violating a novel Bell inequality. Our results provide the first experimental proof-of-principle of generalizations of Bell's theorem for networks, a topic that has attracted growing attention and promises a novel route for quantum communication protocols.

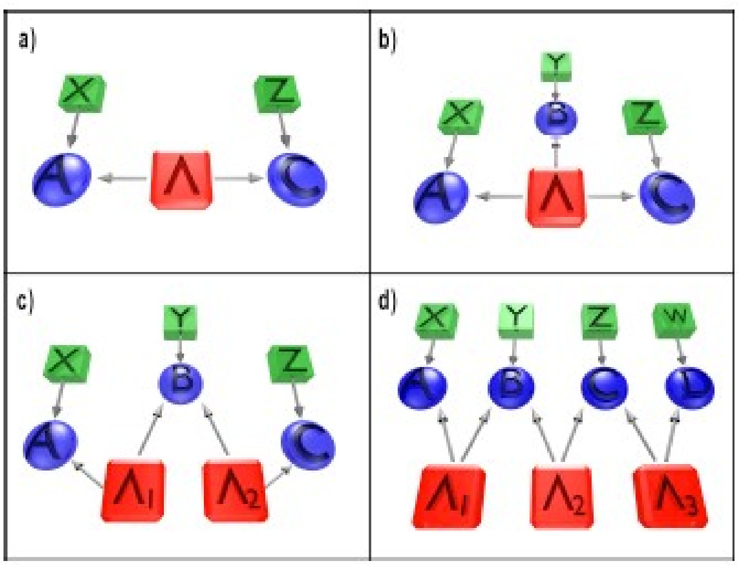

Figure 1: Representation of the causal structures underlying the networks as directed acyclic graphs. Nodes in the graph represent the relevant random variables in the network and the arrows account for their causal relations. a) Bipartite Local Hidden Variables (LHV= model. b) Tripartite LHV model. c) Tripartite scenario with two independent local hidden variables, i.e. Bilocal LHV model. d) Possible extension of the bilocal model to a linear chain of four stations with three independent local hidden variables.

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Quantum-light channels in the atmosphere

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Many fundamental and applied experiments in quantum optics require transferring nonclassical states of light through large distances. In this context the free-space channels are a very promising alternative to optical fibers as they enable establishing communications with moving objects, using satellites for global quantum links and also a number of other interesting possibilities. For such channels the atmospheric turbulence is the main disturbing factor, which should be considered while planning the corresponding experiments.

Atmospheric turbulence is a reason of random fluctuations of the beam-centroid position and the beam shape. This leads to so-called geometrical losses, which consist in the fact that only a part of the beam is transfered through the receiver aperture. The corresponding transmission efficiency appears to be a fluctuating parameter. Our study addresses to main questions: first we consider how fluctuations of the transmission efficiency affect the nonclassical properties of the transmitted light in the case of discrete-variable, cf. Ref. [1], and continuous-variable, cf. Ref. [2, 3], protocols. Second, we consider models for the probability distribution of the transmittance. One model describes nonclassical light under conditions when the atmospheric turbulence results in beam wandering only [4]. Another model, cf. Ref. [5], considers also random fluctuations of the beam shape. We discuss the applicability of both models for conditions of weak and strong turbulence, for different propagation distances, and for different designs of optical experiments.

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Higher-order uncertainty relations for polarization operators

Ulrich Seyfarth

In the past decades experimental techniques in the area of quantum optics have undergone a considerable progress in the ability of controlling and measuring quantum systems very precisely, which asks for pushing the theoretical basis for future steps.
Quantum uncertainty relations give limitations in the accuracy of quantum states. In this contribution we focus on uncertainty relations for polarization operators, where we derive a recipe to generate the higher-order uncertainty relations for polarization operators. The uncertainty relations can be derived for shrinked operators which are useful in the context of different applications.

Hong-Ou-Mandel interference in an integrated quantum optical waveguide device

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Integrated quantum optics can be considered as one of the most active and promising fields of research. Such kind of technologies provide a fruitful and attractive platform for the realization of a wide range of functionalities including quantum simulations, boson sampling, quantum computations, and quantum communication processing. An important and essential element in a computational photonics infrastructure is a quantum interferometer based on the Hong-Ou-Mandel (HOM) interference. A bulk HOM interferometer includes several quite large optical elements which makes it difficult to use and combine them in compact quantum computational circuits. Technologies that allow to realize quantum optical functionalities in small integrated systems are much more promising in this respect.

In this work, we present a theoretical description of a HOM interferometer that can be realized in an integrated quantum optical chip based on, e.g., $LiNbO_3$ waveguide technology. The entire interferometer including several optical elements and the generation of photon pairs via parametric down conversion can be incorporated on a single chip using available fabrication techniques. Our theoretical approach is based on unitary transformations which describe the action of the optical elements and can easily be generalized to more complicated systems. The possibility of observing HOM interference in a fully-integrated device using typical experimental parameters is demonstrated and the dependence of the HOM dip profile on the system parameters and the influence of imperfections of the optical elements on the total coincidence probability is analyzed.

From Ghost Imaging to Turbulence-free Camera

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Abstract

The first ghost imaging experiment was demonstrated in 1995 by taking advantage of the nonlocal behavior of an entangled photon pair. Ten years later, in 2005, we found that the nonlocal interference of a random pair of photons in the thermal state, such as that of the sunlight, is also able to produce ghost image. Inspired by ghost imaging, a new type of camera, which measures photon number fluctuation correlation, has been discovered and commercially developed recently. This camera has the following advantages over the classic imaging technology: (1) the image of the camera is insensitive to any atmospheric turbulence, i.e., turbulence-free; (2) the imaging resolution of the camera, in principle, is determined by the angular diameter of the light source. These properties are particularly attractive for sunlight long distance imaging, such as satellite imaging: the angular diameter of the sun is $\sim$ 0.53 degree, providing in principle a turbulence-free resolution of 200μm for any object on earth at any distance without the need of huge lenses. How does a random pair of photons produce such turbulence-free image? Who is responsible for this "beyond Rayleigh limit" point-to-spot image-forming correlation? This talk will address these fundamentally interesting and practically useful physics.

Quantum enhanced holometer

S. P. Tekuru

We study in detail a system of two interferometers aimed at detecting extremely faint phase fluctuations. This system can represent a breakthrough for detecting a faint correlated signal that would remain otherwise undetectable even using the most sensitive individual interferometric devices, as in the case of so-called holographic noise. The signature of this kind of noise emerges as a correlation between the output signals of the interferometers. On the other hand, when holographic noise is absent one expects uncorrelated signals since the time-averaged fluctuations due to shot noise and other independent contributions vanish (though limiting the overall sensitivity). We show how injecting quantum light in the free ports of the interferometers can reduce the photon noise of the system beyond the shot noise, enhancing the resolution in the phase-correlation estimation. We analyze the use of both the two-mode squeezed vacuum and two independent squeezed states. Our results confirm the benefit of using squeezed beams together with strong coherent beams in interferometry. We also investigate the possible use of the two-mode squeezed vacuum, discovering interesting and unexplored areas of application of bipartite entanglement, in particular the possibility of reaching in principle a surprising uncertainty reduction.

Witnessing entanglement with the Fisher information:

from metrology to topological quantum phase transitions.

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The Fisher information (FI) can witness multipartite entanglement. This sheds light on a profound relation between the distinguishability of quantum states (characterized by the FI through the Cramer-Rao theorem), and entanglement. The framework encompasses quantum technologies for metrology and interferometric phase estimations, foundational problems ranging from the quantum Zeno dynamics to Bell nonlocality up to the characterization of topological quantum phase transitions.

Adaptive Measurements in Experimental Quantum Process Tomography

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Keywords:
adaptive quantum tomography
bayesian inference

We discuss experimental quantum process tomography based on adaptive Bayesian inference.

We have implemented an adaptive measurement scheme for reconstruction of the action of arbitrary quantum channels on single qubits encoded in polarization of photons. Both trace-preserving and lossy processes are realized and reconstructed. We demonstrate a qualitative improvement in estimation precision in comparison with ordinary tomographic protocols. The advantage of the adaptive protocol is most significant for unitary and close to unitary processes.

An important point is that adaptive tomography is less sensitive to instrumental errors. We have studied the tomography performance in the case of artificially introduced noise and instrumental errors and have observed that the 'noise floor' for the adaptive protocol is lower. We have proposed and tested validation criteria, allowing an experimentalist to detect the presence of instrumental errors in measurements and to quantify the maximal achievable precision for the tomographic reconstruction of a quantum process. We also develop a general paradigm for the implementation of self-learning measurement apparatus which is able to avoid noisy measurements and to choose an optimal estimation strategy at the same time.

We also discuss the application of adaptive machine-learning algorithms to characterization of integrated-optical devices. We experimentally demonstrate fast techniques for calibration of actively tunable complex integrated interferometers fabricated by femtosecond laser writing. We further outliner the path towards implementing adaptive self-learning measurements in a fully integrated optical framework.

Quantum Information Resources in two-mode Gaussian Open Systems

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Progress in the development of quantum information theory came from a resource theory approach to quantum entanglement. When restricted to local operations and classical communication (LOCC), entanglement can be regarded as a resource for quantum information processing tasks. An active field of research is the extension of this framework to general quantum correlations such as discord and coherence. Most work however is restricted to the discrete case, leaving out continuous variable systems necessary for quantum optics.

Recently, a framework for analyzing resource theories was developed, based on so called resource destroying maps. This class of maps leave resource-free states unchanged but erase the resource stored in all other states. They can be used to define a class of simple resource measures that can be calculated without optimization, and that are monotone non-increasing under operations that commute with the resource destroying map.

In this sense, we apply the theory of resource destroying maps to the dynamics of two-mode Gaussian open systems, described by the Gorini-Kossakowski-Lindblad-Sudarshan (GKLS) quantum master equation. Based on the theory of completely positive quantum dynamical semi-groups, GKLS gives a fully analytically solvable description of the irreversible time evolution of an open system.

Using measures that require no optimization, we compute the evolution of quantum discord and coherence for a system consisting of two non-interacting and non-resonant bosonic modes, embedded in a thermal environment. Depending on the choice of resource destroying map and the geometry of the resource-free set, different measures for quantum information resources can be defined.

Phase Hologram with Classical Light

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Spatial phase of light carries broad information about properties of encountered medium. By obtaining phase profile of an interacting beam, many precise measurements become available, such as interferometric measurement of surface curvature or accurate measurements of optical density. These analyses require however high coherence between the beam passing through a medium and the reference beam. Problems arise when investigated medium/process induces random changing phase delay, which is faster than capability of our measurement. This will average the signal and erase all spatial phase information.

Nevertheless, higher order correlations might be resistant to the floating phase. As presented in a recent paper: Hologram of a Single Photon[1] (HSP) - such higher order correlations carry full information about the phase structure of a light beam. That method is based entirely on quantum light (pairs of single photons) and Hong-Ou-Mandel effect. In our experiment we show how to obtain a similar effect by using classical light (Coherent states) to regain holograms with visibility near the theoretical maximum of 50%. Obtained holograms resemble those created in HSP. Presented approach requires a significantly less complicated setup and can be used to measure sample in a notably shorter time.

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Second order phase holograms without coherence between the sources

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Spatial phase of light carries vital information about properties of an encountered medium. By obtaining a phase profile of an interfering beam, many precise measurements become available, such as interferometric measurement of a surface curvature or accurate measurements of spatially varying refraction index of materials. These methods require however high coherence between the beam passing through a medium and the reference beam. Problems arise when investigated medium or process induces random changing phase delay, which is faster than capability of our measurement. This averages the signal and erases all spatial phase information.

Nevertheless, higher order correlations are resistant to the fluctuating phase between the interfering beams. As presented in a recent paper: Hologram of a Single Photon[1] (HSP) – such higher order correlations carry full information about the phase structure of a light beam. That method is based entirely on quantum light (pairs of single photons) and Hong-Ou-Mandel effect. In our experiment we show how to obtain a similar effect by using two classical light sources (coherent states), with erased coherence between them, to regain holograms with visibility near the theoretical limit of 50%. Obtained holograms resemble those created with single photons with the HSP method. Notably, presented approach requires a significantly less demanding setup and can be used to measure alteration of phase profile due to propagation through nonuniform or turbid samples in a relatively short measurement time duration.

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[1] R. Chrapkiewicz et al. Nature Photonics 10, 576579 (2016)

Photonic quantum information and metrology: highresolution quantum optical coherence tomography and a photonic quantum circuit for CSWAP

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In this talk, we report our recent progresses on quantum measurements and photonic quantum circuits.

Recently, the application of quantum features to metrology has attracted much attention. Quantum optical coherence tomography (QOCT), which utilizes two-photon interference between entangled photon pairs, is a promising approach to overcome the problem with optical coherence tomography (OCT): As the resolution of OCT becomes higher, degradation of the resolution due to dispersion within the medium becomes more critical [1]. In the first part, we report on the realization of 0.54 μm resolution two-photon interference, which surpasses the current record resolution 0.75 μm of low-coherence interference for OCT [2]. In addition, the resolution for QOCT showed almost no change against the dispersion of a 1 mm thickness of water inserted in the optical path, whereas the resolution for OCT dramatically degrades. For this experiment, a highly-efficient chirped quasi-phase-matched lithium tantalate device was developed using a nano-electrode-poling technique. The results presented here represent a breakthrough for the realization of quantum protocols, including QOCT, quantum clock synchronization.

In the second part, we report a realization of the Fredkin gate using a photonic quantum circuit [3], following the theoretical proposal by Fiurasek [4]. We achieve a fidelity of 0.85 for the classical truth table of CSWAP operation and an output state fidelity of 0.81 for a generated 3-photon Greenberger-Horne-Zeilinger (GHZ) state. We also confirmed that the gate is capable of genuine tripartite entanglement with a quantum coherence corresponding to a visibility of 0.69 for three-photon interferences. From these results, we estimate a process fidelity of 0.77, which indicates that our Fredkin gate can be applied to various quantum tasks.

We may briefly introduce our other recent works on quantum information science [5-7].

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Remote sensing and quantum logic simulations based on second order interference with a single chaotic source

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In the mid fifties Hanbury-Brown and Twiss (HBT) proposed to measure the angular dimension of stars by retrieving second-order interference in the absence of first-order interference [1,2].

We describe here a novel interference scheme based on the use of two unbalanced interferometers at the output ports of a balanced beam splitter in a HBT scheme with a single thermal source at one of the beam splitter input ports [3]. Second-order interference is predicted to occur between light propagating through two paths that fall outside the coherence length of the thermal source. Each interfering path is made of two disjoint, but correlated, optical paths, going from the source to a distant detector after passing though a specific arm (long or short) of the two unbalanced interferometers. The unbalancing between the long and the short arm of the interferometers is such that no first-order interference exists at each detector, separately. However, a counterintuitive second-order interference between light propagating through the two pairs (long-long and short-short) of disjoint optical paths, is predicted to appear by measuring the correlation between the fluctuations in the number of photons at the two detectors. Differently from all previous schemes based on the use of multiple incoherent sources, here second-order interference in the absence of first-order interference is enabled by the use of a single chaotic source.

Similar to HBT interferometry, this novel interference phenomenon leads to a deeper understanding of quantum optics, and has the potential to give rise to new technological developments. Here, we demonstrate how this effect, described also in the spatial domain [4], enables remote sensing applications and the simulation of quantum logic operations with a single chaotic source [3,4]. In particular, we show how this effect can be used to simulate a controlled-NOT gate [3,4]. This has been recently demonstrated experimentally in Ref. [5]. We also describe how this interference phenomenon can be employed to monitor the transverse position and the spatial structure of two distant double-slit masks [4]. This has been recently verified experimentally in Ref. [6].

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Spectrally resolved white-light quantum interferometry for high-accuracy chromatic dispersion measurements

Sebastien Tanzilli

Quantum optical metrology exploits superposition of N-photon number states in order to perform phase-sensing with increased precision compared to classical measurements involving N photons.
In this talk, I will first introduce how to generate particular photonic entanglement, i.e. an energy-time entangled 2-photon N00N state, relying only on telecom-compliant guided-wave photonics.
I will further demonstrate how this state can be advantageously exploited for inferring optical material properties thanks to a dedicated white-light quantum interferometry setup.
Notably, I will show that measuring chromatic dispersion in a 1 m long standard fibre leads to a 2.6 times improved precision compared to itâ€™s classical counterpart.

Joint measurement of complementary observables in moment tomography.

Teo Yong Siah

In the published articles found in Sci. Rep. 5, 12289 (2015) and Phys. Rev. Lett. 117, 070801 (2016), we theoretically and experimentally compared the moment reconstruction performance of two popular continuous-variable (CV) measurement schemes: homodyne and heterodyne (double homodyne) detections.
We found that despite the presence of Arthurs-Kelly type noise that is inherent in the joint measurement heterodyne scheme, for single-mode central-Gaussian states, the heterodyne scheme still results in second-moment estimators that are more accurate than the homodyne scheme for a wide range of the squeezing strength and temperature.

Here, we proceed to generalize the moment-reconstruction performance of both CV schemes to arbitrary quantum states and introduce optimal moment estimators that optimize the performance of the respective schemes for any given data. In the large-data limit, these moment estimators are as efficient as the maximum-likelihood estimators. We then illustrate the superiority in accuracy of the heterodyne measurement for the reconstruction of the first and second moments by analyzing Gaussian states and many other significant nonclassical states. These results are natural extensions to those for central Gaussian states.

Coauthors: C. R. Muller, H. Jeong, Z. Hradil, J. Rehacek, and L. L. Sanchez-Soto

Engineering of Spectral Properties of Non-classical Squeezed States of Light using a Nonlinear Interferometer

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Squeezed states of light are very attractive and perspective non-classical states for different applications in modern quantum optics. They are known to be characterized by strong correlations or “entanglement” between photons both in the frequency and space domain and therefore appear to be a very promising tool for quantum information. Many papers are aimed to describe theoretically the spatial and frequency correlations of photons in a bi-photon pair with the perturbation theory being used. In the case when the nonlinear signal is stimulated by a rather intensive pump a multiphoton squeezed vacuum state can be generated. This state is referred to as a macroscopic non-classical state of light since the number of photons can be huge and numerous correlations between many photons take place. In this case new experimental methods aimed to control the spectral features of the generated squeezed light are of great importance. Moreover in such “high-gain” regime the perturbation theory is no more valid and new theoretical approaches able to describe the spectral properties of the generated squeezed vacuum and strong correlations between many photons are of great demand.

In our work we investigate both theoretically and experimentally the spectral features and correlations in macroscopic (bright) squeezed quantum states of light generated in high-gain parametric down-conversion process. To describe theoretically the spectral features of parametric squeezed light we develop a generalized fully analytical approach, based on the concept of independent collective (Schmidt) modes and valid for the cases of both weak and strong nonlinear interaction. Such possibility is based on the known Schmidt decomposition procedure. In the frame of the Heisenberg representation we obtain the fully analytical solution for the evolution of the photon-creation operators in different frequency Schmidt modes and calculate different characteristics measured in experiment. To control and flexibly change the spectral properties of the generated non-linear light we use a developed method based on an interferometer consisting of two nonlinear crystals with a dispersive medium separating them. The dispersive medium provides a stretching of the signal pulse and the time-delay between the signal and the pump and allows us to select a band of the frequency spectrum to be exponentially amplified in the second crystal. Significantly different spectra and mode content of the non-linear signal are obtained for rather low and high intensity of the pump pulse. In the high-gain regime the possibility to generate two-color parametric down-conversion is presented. At the same time significant narrowing of the spectral peaks is observed. Moreover we have shown that under certain conditions the used two crystal non-linear interferometer gives rise to the dramatically narrow single peak of the frequency spectrum of the generated squeezed light that correspond to the generation of mostly single frequency mode radiation. Thus the suggested method based on two separated crystals provides control and engineering the spectrum of the generated BSV light by timing of the pump. The obtained results are understood and explained in terms of the introduced Schmidt modes in the frame of our developed theory and a very good agreement between the theoretical predictions and experimentally observed results is found. Alternative simplified theoretical approach based on the sequential amplification of the nonlinear signal in two separated crystals is developed and compared with the general theory and experimental data.

Single-photon sources with colour centres in diamond

P. Traina

Disposing of efficient deterministic single photon sources (SPS) is an element of the utmost interest for several applications ranging from quantum metrology (redefinition of candela) to quantum technologies. The best state-of-the-art SPSs are non-deterministic, which limits their range of use. In principle, SPS based on colour centres in diamond (CCiD) could lead to deterministic efficient sources. INRiM single-photon-sensitive confocal microscopy facilty is addressed to the characterization of several types of CCiD as SPS and to their exploitation. A NIR pulsed single photon source, based on a recenltly reported family of CCiD where the emission is optimized through a solid immersion lens directly nanofabricated in the diamond bulk has been realized. Several applications have been implemented in order to exploit CCiD properties to realize improved SPSs.

Quantum enhanced holometer

Paolo Traina

The dream of building a theory unifying general relativity and quantum mechanics, the so called quantum gravity (QG), has pushed theoretical physics research for decades. However, for many years no testable prediction emerged from these studies. Several QG theories predict non-commutativity of position variables at Planck scale inducing a slight random wandering of transverse position (called "holographic noise").

The first results of the Fermilab Holometer , a pair of ultra-sensitive coupled 40-m-long Michelson interferometers built to measure the possible presence of the "holographic noise", while obtaining sensitivity to cross-correlated signals far exceeding any previous measurement in a broad frequency band, exclude the existence of this exotic noise to a 4.6σ significance[1].

On the other hand, a sub-shot-noise phase measurement in a **single** interferometer (e.g. gravitational wave detector) exploiting squeezed light was suggested [2,3] and recently realized [4], ultimately leading to the groundbreaking detection of gravitational waves [5].

Here we discuss the advantages [6] of introducing the use of quantum light in a holometer-like experiment and prompted by these considerations we present the efforts to realize an analogous system on a table-top scale with the aim of reaching, in a forseeable future, a phase sensitivity almost comparable with the one obtained at Fermilab.

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Coincidence Detection of Spatially Correlated Photon Pairs with a Novel Type of Monolithic Time-Resolving Detector Array

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Spatially entangled photon states are used in experiments addressing fundamental properties of quantum mechanics as well as practical applications [1]. Thereby, the use of these states demands for time-saving detection mechanisms, capable of measuring coincidences between spatially separated photons with high spatial and temporal resolution. In this work, we demonstrate coincidence detection of spatially correlated photon pairs by means of the SPADnet-I sensor [2], a fully digital 8×16-pixel single photon detector array in CMOS technology developed for medical applications. It enables per-pixel time stamping with 265 ps resolution combined with a high frame rate of 500 kfps [3]. Commonly used optically or electrically amplified CCD based systems exhibit magnitudes lower frame rates and temporal resolution.

In order to show the capabilities of the detector, we measure the spatial second-order correlation function of a spontaneous parametric down-conversion (SPDC) source at different configurations. In the experiment, a periodically poled $KTiOPO_4$ nonlinear crystal (NLC) is phase-matched for collinear, frequency-degenerate type-0 emission and pumped by a 405 nm CW laser. The center transversal plane of the NLC is imaged to the detector plane with a telescope with a magnification factor $m=8$. For a narrow spectrum around 810 nm, the spatial second-order correlation function in the detector plane is then given by

$$G^{(2)}(\Delta\rho) \propto \left| \int d^2q\, \Lambda(q,-q)\, H(q,z)\, H(-q,z) \exp(-i q \Delta\rho / m) \right|^2$$

where $\Delta\rho = \rho_1 - \rho_2 = (\Delta x, \Delta y)$ denotes the distance between transverse positions in the detector plane. Further, the function $\Lambda(q,-q)$ is the two-photon joint momentum amplitude given by the SPDC process determined by the NLC temperature dependant phase-matching, and where the explicit perfect anti-correlation of the transversal wave-vectors q of the two emitted photons is given under the approximation of a plane wave pump field. Measurements in transversal planes shifted along the optical axis by a distance z is implemented by the free-space propagator H.

Measurements of $G^{(2)}$ for different NLC temperatures and different transversal measurement plane positions are performed and compared to theory, see Fig. 1. These consist of 54 M frames acquired in 165 s which are evaluated for coincidence events. The detector temporal resolution of 265 ps is verified in path delay experiments.

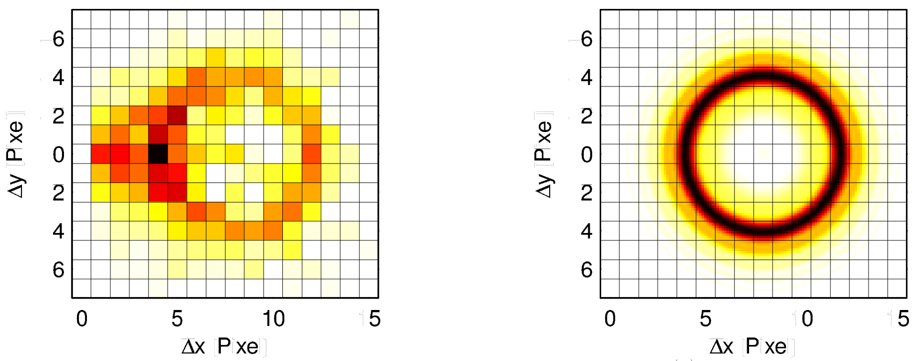

Fig. 1. Experiment (left) and theory (right) of the second-order correlation function $G^{(2)}$ measured in a transversal plane 10 mm in front of the crystal. Distortions at low Δx are explained by cross talk events between adjacent pixels.

Currently, the sensor is not optimized with regard to the photon detection efficiency for the wavelength used in this experiment and it shows a high cross talk between adjacent pixels distorting the measurements. Nevertheless, the here presented results already demonstrate the potential of the technology for correlation measurements in quantum optics. A next generation detector aiming at a higher detection efficiency, higher pixel density, more optimal duty cycle and with reduced cross talk is currently under development.

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Relativistic Effects investigated along Space Quantum Channel

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Space Quantum Communications are considered as a novel arena for both providing the way to realize tests on the interplay of Quantum Physics and Gravity on very long scale and for terminals in relative motion as well as to provide a network of secure communications on planetary scale.
In the perspective to extend the realm of Quantum Communications toward larger distances, we extended the single photons exchange, initially demonstrated for Low Earth Orbit orbits to a source in Medium Earth Orbit, with a slant distance from the satellite to the station of over 7000 km.
Moreover, the exchange of qubits along Space channels was experimentally demonstrated with quantum bit error rate (QBER) low enough to envisage the realization of global secure communications based on QKD.
However, the different conditions of the space terminal with respect to the ground one, an in particular a constantly varying relative velocity of the order of several km/s and the different gravitational potentials are providing a novel tool for the experimental investigation on Quantum Physics in Space.
Here we report on the recent experiments on the relativistic transformation of the phase of a flying time-bin qubit along a 5000 km path, together with a general perspective of the research area.

These QC experiments were realized at MLRO - Matera Laser Ranging Observatory of the ASI Italian Space Agency, in Matera, Italy.

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Optimal estimation of Entanglement and Discord

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In the last decades, Quantum Information (QI) [1] became of great interest for the scientific community, for both pure academic results and potential impact in the technological development of modern society, allowing the development of new quantum technologies like Quantum Communication, Quantum Computation and Quantum Metrology.
The amount of Entanglement and other non-classical correlations, e.g. Discord, in a quantum system plays a crucial role in QI. In particular, entangled two-photon quantum systems represent a fundamental tool in many QI.
In quantum mechanics, a state is completely described by its density matrix, with which we are able to calculate the amount of Entanglement or Discord [2] within such state. However, the experimental technique for the density matrix reconstruction, the quantum state tomography [3], requires a large number of measurements on identical copies of the state, and is computationally expensive in many cases (e.g. entangled states).
In this work, the goal is to implement a new technique to estimate several quantum parameters for specific families of two-photon states, requiring a lower number of measurements with respect to quantum state tomography. In particular, by taking advantage of (partial) *a priori* knowledge of the state we introduce and test estimators for Negativity [4], Concurrence [5] and Log-Negativity [6] (quantifying Entanglement), and Quantum Geometric Discord [7] (estimating Discord).
For each of these parameters, we introduce two estimator, one optimal (i.e. characterized by the lowest statistical uncertainty achievable, determined by the saturation of the quantum Cramér-Rao bound [8]) and one non-optimal.
We test the proposed estimators on eleven different two-photon states, represented by statistical mixtures of a maximally-entangled two-photon state and a completely decoherent one, obtaining in each case experimental results in good agreement with theoretical predictions.

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Entanglement and Extreme Spin Squeezing of unpolarized states

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With an interest towards fundamental questions in quantum physics, as well as quantum information processing applications, larger and larger entangled quantum systems have been realized with photons, trapped ions, and cold atoms. In particular, entanglement is also necessary to reach the maximum sensitivity in a wide range of interferometric schemes in quantum metrology. Hence, the verification of the presence of entanglement is a crucial but exceedingly challenging task, especially in an ensemble of many, say 10^3-10^12 particles.

In the many-particle case, especially in large ensembles of cold atoms, it is typically very difficult or even impossible to address the particles individually, while measuring collective quantities is still feasible. In this context, one of the most successful approaches to detect entanglement relies on inequalities involving mean values and variances of collective spin components.

Traditional approaches in this respect [1] are best suited for states with a large collective spin polarization and a small variance in one orthogonal direction, so called “spin squeezed” in the context of metrology [2]. Spin squeezing has been demonstrated in many experiments, from cold atoms to trapped ions, magnetic systems and photons. In several experiments the “entanglement depth” was determined, i.e., the minimal number of mutually entangled particles consistent with the measurement data, reaching to the thousands [3].

Here, we present a generalization of such spin squeezing criteria to detect the depth of entanglement in macroscopic ensembles of spin-j particles [4].

We show the optimality of our criterion and how to evaluate it numerically even for systems of very many particles. We also show that it outperforms past approaches, especially in practical situations where noise is present.

The class of states detected goes beyond traditional spin-squeezed states and includes, in particular, unpolarized states. Especially, we extend the concept of spin squeezing to Dicke states, which are being produced in experiments with photons and Bose-Einstein condensates [3], since their multipartite entanglement is robust against particle loss, and they can be used for high precision quantum metrology.

We also derive analytic lower bounds based on the linearization of our criterion, which produce as a by-product also an analytic lower bound to the well-known criterion derived in [1]. Finally, we also discuss the extension of our results to systems with fluctuating number of particles.

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Enhancing sideband cooling with feedback-controlled light: quantum nanomechanical resonators for testing deformed commutators

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Feedback loops based on real-time continuous measurements are commonly used for stabilisation purposes, and they have also been successfully applied to the stabilisation of quantum systems. Typically a system is continuously monitored via a probe electromagnetic field, and the acquired signal drives the actuator which in turn drives the system to the desired target. Here we demonstrate a novel closed-loop control scheme in which the actuator acts on the probe field itself in order to engineer its phase and amplitude fluctuations. The resulting feedback-controlled in-loop field is then exploited to manipulate the system and improve its performance. In-loop optical fields have already been employed in the negative feedback regime for noise suppression and stabilization, the so-called â€œsquashingâ€.Â Here, instead, we operate in the â€œanti-squashingâ€ regime of positive feedback and increased field fluctuations, and demonstrate the potentiality of this new technique by improving the sideband cooling of a nanomechanical membrane by 7.2 dB. In the fully quantum regime, feedback-controlled light would allow going below the quantum back-action cooling limit, similarly to what has been recently achieved by injecting squeezed vacuum fluctuation, but without the complications inherent to the use of quantum nonlinear devices. The proposed feedback architecture can be used in a broad range of applications, whenever a system of interest is linearly coupled to an electromagnetic field subject to a phase-sensitive measurement.

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Nonclassicality versus Entanglement of Radiation Fields

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Quantum properties of light are considered from the viewpoints of nonclassicality and entanglement. For this purpose, nonclassicality quasiprobabilities are introduced which are accessible in experiments and uncover the quantum signatures in terms of negativities. As an example, the quantumness of squeezed light has been experimentally visualized in Rostock by direct sampling of the corresponding quasiprobability [1].

Multipartite entanglement of complex quantum states is studied by the method of optimized entanglement witnesses. Based on data for a 10-mode quantum state recorded in Paris, the entanglement of all 115974 partitions has been verified [2]. In addition, it is shown that an experimental state, which fails to show so-called "genuine multipartite entanglement", can be multipartite entangled in different partitions and their convex combinations [3]. For high-order partitions, we get increasing statistical significances of our entanglement tests.

The notion of nonclassicality is generalized to the description of space-time dependent quantum correlations of light [4]. The corresponding criteria for such quantum correlations are considered, for the example of a fully dephased two-mode squeezed vacuum. Based on experiments in Paderborn, the quantum correlations have been verified by joint click correlation measurements with a time-multiplexing device [5].

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Quantum Imaging with Incoherent Light

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Most of present-day imaging methods rely on coherent scattering processes [1], therefore great efforts are undertaken to maintain the first-order coherence of the radiation field upon propagation from the source through the sample up towards the detector. On the other hand, in the interaction of light with matter incoherent scattering processes are often inevitable and even sometimes predominant leading to a background that obstructs the coherent diffraction signal [2,3]. In this talk we show that higher-order intensity correlations of incoherently scattered light can be used to reveal the full information about the arrangement of the scatterers, eventually reaching a spatial resolution even below the Abbe limit. The method goes beyond the landmark intensity correlation measurements of Hanbury-Brown and Twiss [4] or former approaches to image one-dimensional source distributions using higher order correlations [5,6], extending the technique to x-ray structure determination of arbitrary two-dimensional source arrangements which incoherently scatter XUV radiation. The scheme is illustrated with a non-periodic two-dimensional distribution of incoherent scatterers resembling an artificial benzene molecule. This constitutes a new approach towards structure determination, exploiting higher degrees of coherence under conditions that are generally considered detrimental for imaging applications.

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Quantum State Tomography

What to do with negative eigenvalues

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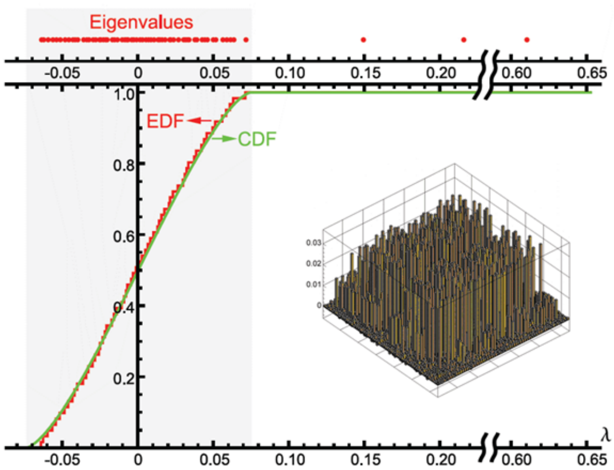
Experimental quantum state tomography is racked with unphysical solutions, that means with state estimates with negative eigenvalues. We show that the statistical nature of measurements alone easily causes negative eigenvalues. The usual multinomial or Poissonian noise caused by a finite number of samples of measurements results in eigenvalue distributions converging to the Wigner semicircle distribution for already a modest number of qubits. This fact can and has to be taken into account for the evaluation of tomographic data.

Knowing the effect of statistical noise enables the distinction of eigenvalues, which are statistically significant and can be trusted and which are insignificant or just the result of statistical effects. This allows a new procedure to obtain a physical estimate with minimal numerical effort, without constrained optimization, thereby also avoiding biased estimation.



Quantum State Tomography of a six qubit Dicke state: Eigenvalues (red points) and the support of the assumed Wigner semicircle distribution (gray shaded area) already indicate which eigenvalues are statistically relevant and which aren't. A hypothesis test is applied to compare the empirical distribution function (EDF) (red stepped curve) of the smallest 61 eigenvalues with the cumulative distribution function (CDF) of the Wigner semicircle distribution (green smooth curve) with the width R = 0.0745, as determined by the statistics of the measurement. Averaging over all thus identified statistically irrelevant eigenvalues results in a rank 3 state admixed with a small contribution of white noise ($c = 4\cdot10^{-4}$), in excellent agreement with what to be expected for the state obtained from parametric downconversion.

Generation of Mechanical Interference Fringes by Multi-Photon Quantum Measurement

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The exploration of wave phenomena and quantum properties of massive systems offers an intriguing pathway to study the foundations of physics and to develop a suite of quantum-enhanced technologies. Here we present an optomechanical scheme to prepare non-Gaussian quantum states of motion of a mechanical resonator using photonic quantum measurements. Our method is capable of generating non-classical mechanical states without the need for strong single-photon coupling, and is resilient against optical loss and initial mechanical ther- mal occupation. Additionally, our approach provides a route to generate larger mechanical superposition states using effective interactions with multi-photon quantum states. We exper- imentally demonstrate this technique on a mechanical thermal state in the classical limit and observe interference fringes in the mechanical position distribution that show phase super- resolution. We demonstrate our technique by creating thermal Compass states of 4, 6 or 8 nodes. This opens a feasible route to explore and exploit quantum phenomena at a macroscopic scale.

From Mo Zi to the Mo Zi satellite: a brief history of optics in China

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Abstract:

Unknown to many people, the earliest extant record of optics appeared in China [1-2]. In the *Mo Jing* [3], written by Mo Zi who was born in China circa 470 BCE, about 170 years before Euclid, the ancient philosopher not only expounded upon logic, geometry and mechanics, but also described basic concepts of linear optics such as reflection by plane and curved mirrors, refraction, and the camera obscura, all based on actual experiments. Later, Liu An (179-122 BCE) wrote about various optical devices including "burning glasses" made of ice and the earliest surveillance periscope. However, this was followed by a long period during which scientific thought stagnated in China, and it was only after glass lenses were introduced from the west that optics was revived as a field of study. Henceforth, China followed the footsteps of foreign scientists, and has only started to catch up over the last half century. Research in quantum optics also began with knowledge brought back by scholars in the eighties, but with increasing investment in science and technology, Chinese scientists are making great strides forward.

A brief overview will be presented of the history of optics in China, through the development of quantum optics, up to the landmark launch of the Quantum Experiments at Space Scale Satellite (QUESS, nicknamed the Mo Zi satellite) in August 2016.

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Control of spatial features and mode structure of squeezed non-classical light in two-crystal scheme

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Macroscopic non-classical squeezed states of light are widely studied nowadays, as they can be used for many applications, such as quantum imaging, noise reduction measurements, quantum optomechanics and metrology. These states reveal significant quantum features and at the same time can contain big number of photons. The most flexible and promising experimental scheme to generate squeezed states with controllable features is known to be based on two crystal nonlinear interferometer since the spatial and frequency modes of signal and idler beams can be easily changed by varying macroscopic parameters such as the distance between the crystals and the pump power [1, 2]. Such system allows to get many azimuthal modes with different orbital angular momenta [3]. Multimode structure is very important for practical purposes providing large capacity of quantum information.

The two crystal scheme is well studied mainly in the so called high gain regime when only few or even one spatial or frequency mode of squeezed vacuum is predominantly generated [2, 3]. It is also easy to provide theoretical description in the perturbation regime when the pump intensity is low and bi-photon pairs are generated. However the intermediate regime when many photons are generated in many different spectral and spatial modes is of great interest and remains still unexamined. In this work we investigate theoretically spatial properties and mode structure of the multiphoton squeezed parametric light generated in a two-crystal configuration in details. The theoretical approach is based on the Schmidt mode analysis [3] which provides the possibility to calculate analytically all measurable quantities if the Schmidt modes are found.

We investigate the shapes, phases and weights of the found Schmidt modes for the generated parametric down conversion light in dependence on the separation of crystals and pump characteristics. The comparison between the calculated mode content and conventional Laguerre-Gauusian modes obtained from one crystal scheme is made [4]. It is found that for parameters correspondent to most experiments with two crystals the usually used two-photon amplitude function can be significantly simplified. For high distances between crystals analytical expressions of the detected Schmidt modes are found, that are based on the mode structure of one crystal of the same size. It is shown that for the case when the output beam has zero intensity in the center, many radial modes can be obtained in addition to the large number of azimuthal modes. The separability between radial and azimuthal variables is examined. Correlations of photons in the near field and far-field regions are analyzed. Methods to provide a selective amplification of a certain individual Schmidt mode based on the seeding by conventional Laguerre-Gauusian mode with rather simple spatial structure are suggested.

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QUANTUM SYNCHRONIZATION AS A LOCAL SIGNATURE OF SUPER AND SUBRADIANCE

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Abstract:
We study the relationship between the collective phenomena of super and subradiance and spontaneous
synchronization of quantum systems.
To this aim we revisit the case of two detuned qubits interacting through a pure dissipative bosonic environment, which contains the minimal ingredients for our analysis.
By using the Liouville formalism, we are able to find analytically the ultimate connection between these phenomena.
We find that dynamical synchronization is due to the presence of long standing coherence between the ground state of the system and the subradiant state.
We finally show that, under pure dissipation, the emergence of spontaneous synchronization and of subradiant emission occur on the same time scale. This reciprocity is broken in the presence of dephasing noise.

Coherence Power of Quantum Operations

Paolo Zanardi

Given a preferred orthonormal basis B in the Hilbert space of a quantum system we define a measure of the coherence generating power of a unitary operation with respect to B.

This measure is the average coherence generated by the operation acting on a uniform ensemble of incoherent states. We find its explicit analytical form in any dimension and provide an operational protocol to directly detect it.

We characterize the set of unitaries with maximal coherence generating power and study the properties of our measure when the unitary is drawn at random from the Haar distribution.

High-rate semi-device-independent quantum random number generators based on unambiguous state discrimination

Hugo Zbinden, Jonatan Bohr Brask, Anthony Martin, William Esposito, Raphael Houlmann, Joseph Bowles, and Nicolas Brunner

An approach to quantum random number generation based on unambiguous quantum state discrimination (USD) is developed. We consider a prepare-and-measure protocol, where two non-orthogonal quantum states can be prepared, and a measurement device aims at unambiguously discriminating between them. Because the states are non-orthogonal, this necessarily leads to a minimal rate of inconclusive events whose occurrence must be genuinely random and which provide the randomness source that we exploit. Our protocol is semi-device-independent in the sense thatthe output entropy can be lower bounded based on experimental data and few general assumptions about the setup alone. It is also practically relevant, which we demonstrate by realising a simple optical implementation achieving rates of 16.5 Mbits/s. Combining ease of implementation, high rate, and real-time entropy estimation, our protocol represents a promising approach intermediate between fully device-independent protocols and existing commercial QRNGs.

Demonstration of photonic side channel attacks on cipher chips

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Abstract:

Even though quantum key distribution is admitted to be absolutely secure in theory, it is still susceptible to physical attacks on the system. Much research is now being conducted on both active and passive attacks on all cryptographic systems. Optical side channel attacks include both active irradiation to induce faults, and passive observation of photonic emission. In photon emission analysis, first proposed in 2008 [1], photons from a specific part of the cipher chip are selected and analyzed; this has a much better signal-to-noise ratio compared with electromagnetic radiation or power monitoring which focuses on system-wide side channel information leakage of the devices.

We have recently performed an experiment to detection and analyse the photonic emission from CMOS integrated circuits. Using time-correlated single-photon counting, we have measured and analyzed the relationship between the photonic emission and applied voltage, as well as the operations and data processed at the instruction level, of the cipher chip AT89C52 [2]. Furthermore, the number of photons emitted during execution of the AES encryption arithmetic is found to have a linear relationship with the operand Hamming weight. By selecting several groups of plain texts, the AES encryption algorithm key has been successfully cracked [3]. Our results show that photonic emission analysis could be a relatively low cost but effective method for optical side-channel attacks, and could severely threaten the security of not only conventional cipher systems but also quantum key distribution.

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Quantum phase-slip phenomenon in wide superconducting films

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Quantum fluctuations, also called *quantum phase slips*, can suppress the dissipationless electric current in ultra-narrow superconducting nanowires even at comparatively low temperatures, consequently setting the ultimate limit for applications of related superconducting quasi-1D components. In this work, we show that similar effects stimulated and controlled by spin-polarized quasiparticle injection can be observed also in wide quasi-2D superconducting films with the width strongly exceeding the superconducting coherence length ξ.

The injection was realized in bilayers formed by a superconductor (S) and a half-metallic ferromagnetic (F) Co_2CrAl compound known to have metallic density of states in one of the spin subbands and a gap in the density of states in the other spin subband. We used two kinds of S films, Pb, that is a type-I superconductor which interior in the bulk state cannot be penetrated by a weak magnetic field H, and $Mo_{56}Re_{44}$ alloy, a type-II superconductor characterized by the formation of magnetic vortices in an applied field H above a certain critical field strength H_{c1}. It is the primary difference since other parameters of the two materials are similar. Critical temperatures T_c of free S layers are between 7 and 9 K (T_c slightly decreases in proximity with the half–metallic layer); coherence lengths ξ are a bit less than 100 nm; thicknesses of 100 μm-wide S films are of the same scale as ξ and thus they can be considered as 2D-superconductors.

Current-vs-voltage (*I-V*) curves for the SF bilayers usually display a wide transition region between the appearance of a non-zero voltage above the critical current I_c and the completely ohmic behavior representing their normal state. An injection current was applied from one lead of the F layer to one lead of the S strip and *I-V* traces of the $Mo_{56}Re_{44}$ strip were recorded at the bath temperature of 4.2 K with the usual four-terminal measurement technique. After switching on the injection current of the order of several mA, we observed a noticeable suppression effect on resistive *I-V* characteristics with *steps-like features* following the main phase-slip events criteria: (i) a voltage jump at a critical current value; (ii) approximately the same excess current for all resistive branches, and (iii) their resistances follow the universal relation $R_n = nR_0$ where n is integer, the branch number, R_0 = const. An external, comparatively small magnetic field perpendicular to the S plane was applied to study its influence on the S-to-N transition in superconducting strips. For the $Mo_{56}Re_{44}$ alloy, the effect was observed even at H values smaller than H_{c1}. Hence it cannot be related to the direct impact on the superconducting subsystem but rather on the magnetization of different domains within the F strip.

The two studied superconductors exhibit very similar behavior under strong spin-polarized injection despite their fundamental difference, thus strongly supporting emergence of phase-slip lines in wide superconducting films proximized to a half-metallic strip.

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Strongly entangled states of homogenous and heterogeous multipartite systems

Karol Zyczkowski

The Bell states are known to be maximally entangled among all two-qubit states. Furthermore, GHZ states maximize 3-tangle and some other measures of entanglement for thee-qubit systems, since their one-party reductions are maximally mixed.

What are the most entanagled states for homogeneous systems consisting of N systems with d levels each? On one hand the answer may depend on the entnaglement measure used.
On the other hand, already for four-qubit system there are no states, such that any of its two-party reduction, with respect to any possible splitting, is maximally mixed.
We show that such states exist for four qutrits and discuss existence of such entangled multipartite states for heterogeneous systems, consisting of subsystems of a different size.
For instance we present strongly entnagled states for a two-qubit, one-qutrit system, and two-qutrit, one qubit system.