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(*ad memoriam of Carlo Novero*)

Book of Abstracts

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Single quantum gates and Bell's states using the controlled adiabatic evolutions

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Fundamental quantum gates can be implemented effectively using adiabatic quantum computation or circuit model. Recently, Itay Hen combined the two approaches to introduce a new model called controlled adiabatic evolutions [Phys. Rev. A, 022309 (2015)]. This model was specifically designed to implement one and two-qubit controlled gates. Later, Santos extended Hen's work to implement n-qubit controlled gates [Sci. Rep., 15775 (2015)]. In this study, we demonstrate the possibility of preparing Bell's states using the controlled adiabatic evolutions approach, as well we discuss the fidelity results of implementing single quantum gates and Bell's states using the controlled adiabatic evolutions in open systems.

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Engineering Doped Single Crystal Diamond Films for Quantum Applications

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Diamond is a transparent wide band gap material with outstanding optical and electronic properties that are attracting a lot of attention for the development of the next generation of devices. Indeed single crystal diamond provides an ideal host material to incorporate different types of impurities that can drastically modify its properties. The use of dopants such as boron can for example allow tuning the electrical conductivity of the film up to the metallic conduction. In addition nitrogen or silicon are some of the elements that can be introduced in the crystal in order to create optically active centres such as the well-known NV (nitrogen-vacancy) and SiV (silicon-vacancy) defects.

Harnessing the outstanding properties of these colour centres mainly relies on the progresses obtained in the synthesis of high quality and purity diamond material using the microwave plasma assisted chemical vapour deposition technique (MPACVD). Individual or ensembles of NV centres can be produced by nitrogen implantation of high-purity isotopically ^{12}C enriched CVD diamond plates. On the other hand, the direct creation of NVs during growth allows creating defects with improved properties in terms of coherence time and orientation as compared to implantation. The requirements though are very challenging and are setting an increasing pressure to the diamond synthesis capabilities by MPACVD. They include the control of NV creation yield and density over a wide range of concentration, from a few ppb to a few ppm and the control of defects spatial localization both in-depth (creation of delta-doped layers for example) and in-plane (creation of arrays). Moreover the ability to promote one orientation among the 4 possible axes of the NV dipole by growing on specific orientations such as (111) and (113) represents a strong advantage for the foreseen applications.

In this presentation, we will focus on the synthesis of monocrystalline diamond films by MPACVD, highlighting all the constraints inherent to the formation of NV and SiV centres. In particular, the conditions for optimizing the formation and orientation of these defects will be discussed and the role of temperature, substrate orientation and gas composition will be highlighted. We will then extend this discussion to the same material system produced at the nanoscale. In fact CVD grown nanodiamonds, unlike other production methods such as detonation and milling of bulk particles, may allow an unprecedented control over the chemical purity, composition and doping with nitrogen or silicon. These assets make these materials particularly attractive for applications in quantum technologies.

Towards superresolution surface metrology: Quantum estimation of angular and axial separations

Gerardo Adesso

We investigate the localization of two incoherent point sources with arbitrary angular and axial separations in the paraxial approximation. By using quantum metrology techniques, we show that a simultaneous estimation of the two separations is achievable by a single quantum measurement, with a precision saturating the ultimate limit stemming from the quantum Cramér-Rao bound. Such a precision is not degraded in the sub-wavelength regime, thus overcoming the traditional limitations of classical direct imaging derived from Rayleigh's criterion. Our results are qualitatively independent of the point spread function of the imaging system, and quantitatively illustrated in detail for the Gaussian instance. This analysis may have relevant applications in three-dimensional surface measurements.

Quantum nano-optics with diamond color centers and colloidal quantum dots

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Color centers in diamond and colloidal quantum dots represent a promising playground for quantum nano-optics thanks to their unique optical properties and photo stability at room temperature. In particular, the silicon vacancy (SiV) color center is a valuable testbed for quantum optical technologies as most of its fluorescent signal is concentrated in the narrow zero-phonon line, with a room-temperature linewidth down to about 1 nm. Moreover, it exhibits a short excited-state lifetime and a very small inhomogeneous broadening. On the other hand, the multi-particle radiative and non-radiative carrier dynamics of a single colloidal quantum dot (QD) allows to explore a rich photo physics under the largely controllable settings provided by nano-optical fields.

We discuss progress in the production of SiV color centers in ultrathin diamond membranes and strategies for achieving highly efficient light extraction and directional emission of single photons. We show that the emission pattern of the SiV center can be funnelled into a single lobe having a half-width at half maximum as tight as 8 degrees in air, with very good agreement between theory and experiment. Next, we take advantage of gold nano cones for exploring the ultrafast photodynamics of a bare single CdTe colloidal QD. We demonstrate that 99% of the surface defect-state emission can be quenched solely by plasmon coupling and that the band-edge excitonic and biexitonic radiative recombination rates are enhanced by 676 and 293-fold, respectively.

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Testing nonclassicality in lossy transmission and detection systems

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Nowadays, the effective exploitation of quantum resources is often prevented by the presence of noise sources in the transmission channels [1,2] and/or by the nonidealities of the employed detectors [3,4] . As to the former aspect, the main obstacle is given by losses, which can be modelled according to different statistical distributions, such as the log-normal distribution in the case of turbulent media. For what concerns the detection stage, the main limitation is given by the non-unitary quantum efficiency of the detector. In addition, depending on the chosen detector, there could be spurious stochastic effects, such as dark counts, after pulses, cross talk, and saturation effects [5].

In order to address such problems in practical situations, we consider the observation of nonclassical correlations, quantified by the noise reduction factor, between the two parties of a multi-mode twin-beam state in the mesoscopic intensity regime. On the one hand, we focus on the survival of nonclassicality in the presence of asymmetric lossy channels [6] modelled according to some specific statistical distributions. On the other hand, we investigate under which conditions the use of Silicon photomultipliers as photon-number-resolving detectors allows the observation of nonclassical correlations. In particular, we study, both theoretically and experimentally, the role played by the cross-talk effect that affects such detectors [7].

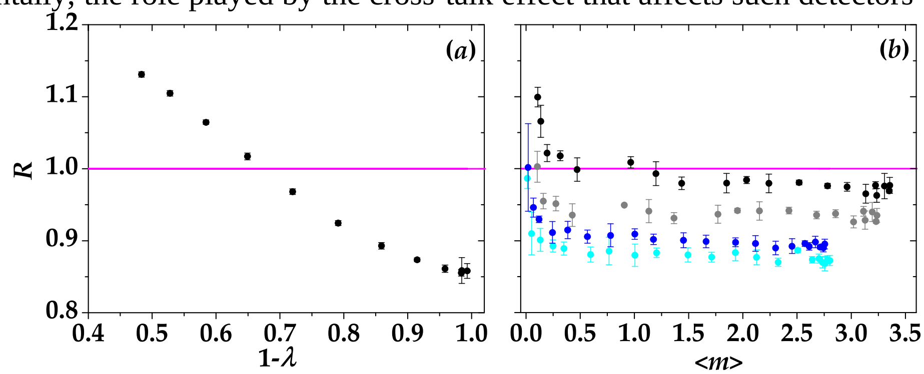

Fig. 1: (*a*) Noise reduction factor in a lossy channel with different truncated uniform distributions. (b) Noise reduction factor for different gate widths over which the output of Silicon photomultipliers is integrated.

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Attaining the ultimate precision bound for estimating parameters on the environment by a quantum sensor

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Controlled quantum spins are sensitive probes of the environment and a powerful tool for characterizing highly complex quantum systems at a molecular or atomic scale. Novel quantum technologies requiring high sensitivity at the nanoscale are based on
quantum spin probes serving as magnetometers, thermometers, sensors for imaging or monitoring biological process. We explore the ability of a qubit probe to characterize unknown parameters of its environment. By resorting to quantum estimation theory, we analytically find the ultimate bound on the precision of estimating key parameters of a broad class of ubiquitous environmental noises which the qubit may probe. By optimizing the dynamical control on the probe under realistic constraints one may attain the maximal accuracy bound on the estimation of these parameters by the least number of measurements possible. Applications of this protocol that combines dynamical control and
estimation theory tools to quantum sensing are illustrated for a nitrogen-vacancy center in diamond used as a probe and for enhancing the resolution of magnetic resonance imaging.

Distributed quantum sensing

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Quantum technology consists very often of networks. Quantum communication is inherently a network while some quantum computing architectures are based on networking to realize scalability. Quantum sensing can be also realized in a networked scheme using entangled states and specialized measurements with applications in e.g. magnetic field mapping and precision clocks.

In this talk, we present our recent work on demonstrating distributed quantum sensing of four delocalized phases with a precision that goes beyond the standard shot noise limit using continuous variable entanglement. We show experimentally that sensing of the delocalized phases using distributed entanglement is superior to using local squeezed state resource. We also show heoretically that the sensitivity is expected to exhibit Heisenberg scaling in the number of sensing nodes, an effect that is similar to the Heisenberg scaling in a multi-pass approach [1].

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Complete identification of nonclassicality of Gaussian states via intensity moments

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We present an experimental method for complete identification of the nonclassicality of Gaussian states in the whole phase space (1). Our method relies on nonclassicality witnesses written in terms of measured integrated intensity moments up to the third order, provided that appropriate local coherent displacements are applied to the state under consideration. The introduced approach, thus, only requires linear detectors for measuring intensities of optical fields, that is, very convenient and powerful from the experimental point of view. Furthermore, utilizing a mathematical equivalence between the description of the coherent displaced Gaussian states generated in the spontaneous parametric down-conversion processes, so called twin beams, and the Gaussian states generated in the corresponding stimulated parametric processes, we show how the stimulated emission can be exploited in the revealing of the entanglement of twin beams by using considered nonclassicality witnesses (2).

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Optimal estimation of parameters encoded in coherent states quadratures

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The quantum estimation theory introduced by Helstrom [2] sets fundamental bounds on the extraction of parameters encoded in quantum systems. Since then, a lot of effort has been deployed in the study of the estimation of classical parameters such as phases encoded in some quantum states [3, 4]. Recently, the problem of estimating parameters introduced with the help of non-commuting generators [5, 6] has also been addressed.
In this context, we consider the problem of encoding and estimating multiple classical parameters in conjugate variables such as the quadratures of the coherent states of light. We derive the Quantum Cramér-Rao bounds (QCRB) for an arbitrary linear encoding of two classical parameters into the quadratures of two coherent states. Furthermore, we present an encoding and estimation protocol that achieves the QCRB for both classical parameters simultaneously. Finally, we generalize our protocol to encode a set of N parameters into a set N of coherent states such that one can always estimate these parameters optimally by simultaneous measurement using a technique involving only beam-splitters. A corollary of our work is the proof of optimality of the measurement scheme proposed by N. J. Cerf and S. Iblisdir [1] in 2001. This problem was left open for a long time.

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Fisher Information with Continuous Variable Quantum Resources

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Squeezed states are a crucial resource for improving the precision of parameter estimation problems [1]. However, the optimal bounds of the Fisher information in continuous variable experiments have, so far, only been abstractly defined and do not account for many important experimental parameters, such as the quantum efficiency and bandwidth of the detector [2]. We show that classical Fisher information calculations can be used to compute these optimal bounds with more applicability to experimental measurement, and this is demonstrated in the case of estimating a modulated optical loss by using an amplitude squeezed coherent state as a probe.

We developed a theoretical model to study the Fisher information on the modulation index δ, where δ represents the fractional modulated loss, illustrated in the inset of Fig. 1. This model accounts for detection efficiency, detection bandwidth and optical power. Normalising to the number of input photons, the per photon Fisher information $FI(\delta)'$ has been plotted in Fig. 1, for both a coherent state (blue) and a 3dB squeezed state (orange). This result indicates that a maximum quantum advantage can be achieved when the applied modulation is at a minimum. These results bring together the theoretical techniques used with discrete variables and the necessary experimental considerations for continuous variable quantum information. This will enable a better understanding of the quantum advantage in precision provided by continuous variable quantum resources, such as squeezing, in metrological applications. An experimental scheme for verifying this bound on the Fisher information will also be presented.

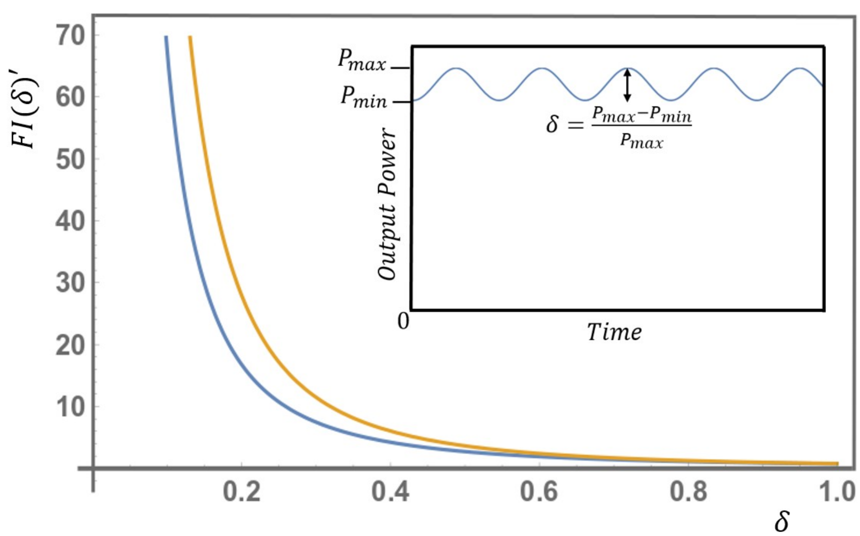

Figure 1: Predicted per photon Fisher information as a function of modulation depth, for a coherent input state (blue) and a 3dB squeezed input state (yellow). Inset: Illustration of how the modulation index relates to the oscillating power.

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Generalizing the CHSH Bell inequality and self-testing of two-qutrit quantum systems

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Introduction. The rapid development of quantum technologies creates an urgent need to design efficient and robust certification methods that would allow the end user of a quantum device to verify whether it operates in a quantum way and cannot be mimicked by purely classical methods. One of such methods, formulated in the cryptographic context, is self-testing [1,2]. It allows for certification of entangled quantum states in quantum devices together with measurements made on it only from the observed non-local correlations. Self-testing is thus another device-independent application of nonlocality.

Results. We first introduce a general class of Bell inequalities in a d-outcome scenario with prime d, which is a modification of the CHSH-d Bell inequality [3], and prove that it is maximally violated by the maximally entangled state of two qu*d*its and quantum observables that form mutually unbiased bases. We thus propose another, next to [4], generalization of the well-known CHSH Bell inequality [5] to d-dimensional quantum systems, which preserves the most important features of the CHSH Bell inequality; for instance, can easily compute its maximal quantum value. Using our inequality we then derive a self-testing statement for qutrit systems which, contrary to the previous approaches [6,7], does not in any way rely on self-testing results for qubit states. That is, we prove that up to local isometries the quantum state maximally violating our Bell inequality is the maximally entangled state of two qutrits, whereas the three measurements performed by each party form mutually unbiased bases. The full version of our results can be found in [8].

Methods. The key method used to derive our results is the sum of squares decomposition of the so-called shifted Bell operator, which allows to determine the maximal quantum violation of a Bell inequality. Importantly, such a decomposition implies certain conditions on a quantum state and measurements violating maximally our Bell inequality. By solving them we obtain the aforementioned self-testing statement for two-qutrit entangled quantum systems.

Discussion. Unlike the previous approaches, we provide the first, to the best of our knowledge, self-testing statement of a composite quantum system of local dimension larger than two that exploits a genuinely d-outcome Bell inequality. It would be certainly of a great interest to generalize our results to any prime local dimension.

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Quantum differential ghost imaging

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Ghost imaging, proposed in 1994 [1] and experimentally demonstrated in the following year [2], is an imaging technique that, exploiting correlated light beams, allows to produce an image of an object by combining information from two light detectors: a multi-pixel detector that does not view the object, and a single-pixel (bucket) detector that does view the object. Many different ghost imaging protocols have been proposed and demonstrated in recent years [3–12]. A particularly interesting protocol is the so called differential ghost imaging. It was proposed and demonstrated in 2010 exploiting bright thermal light [13]. Differential ghost imaging offers a relevant advantage respect to the conventional technique in the cases of small or weakly absorbing objects.

Here, we show a work [14] where: We extend the differential ghost imaging protocol exploiting quantum correlations between twin beams. We develop a comprehensive model taking into account non ideal elements of an experimental apparatus like channels inefficiencies and electronic noise of the detectors. We developed an optimized protocol, able to partially compensate for them, and we perform an experiment to compare it with previous protocols. In order to validate the theoretical model, we perform a set of measurement on calibrated absorbing samples. Then, as an example of possible real application, we reconstruct a complex biological object.

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In-field demonstration of a quantum key distribution system in the metropolitan Florence area

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In a society based on the continuous exchange of sensitive data and information, the importance of secure and trustful communications is essential. Quantum key distribution (QKD) makes it possible to share data in an unconditionally secure way exploiting the basic principles of Quantum Mechanics [1]. During the last 30 years, many QKD protocols have been developed and tested, achieving long distance transmission [2,3] and secret key rates up to hundreds of Mbits per second [4]. However, this technology is still far from a large-scale deployment in existing fiber networks and telecom infrastructures, due to multiple factors: low secret-key rate, limited distance between users, lack of applications, high costs and high requirements in terms of low noise fiber links.

In order to reveal practical issues in real-world deployments, quantum field trials have been implemented by exploiting installed fiber links on a metropolitan scale. Many of these experiments were performed on a dark fiber, thus requiring a dedicated link for quantum key transmission only [5-6].

In this work we report a low-cost field demonstration of a complete QKD system working in the C-band telecom wavelength, performed over an installed fiber situated in Florence. A time-bin three-state protocol with one-decoy state method is implemented in the experiment. As illustrated in Figure 1 a), the experimental setup consists of a transmitter (Alice), working at ITU-T ch 21, and a receiver (Bob) connected by a metropolitan dark-fiber link in a loop-back configuration. The total distance covered in the fiber link is about 40 km, with an overall transmission loss of 21 dB. Secure key generation of 5.23 kbps (in the finite key scenario) is achieved, with simultaneous transmission of a classical synchronization signal, at a different wavelength (ITU-T ch 51 @ -29 dBm input power), through the same fiber. In Figure 1 b) we report the secret key rate and the bit error rate, measured for several hours to prove the stability of the apparatus.

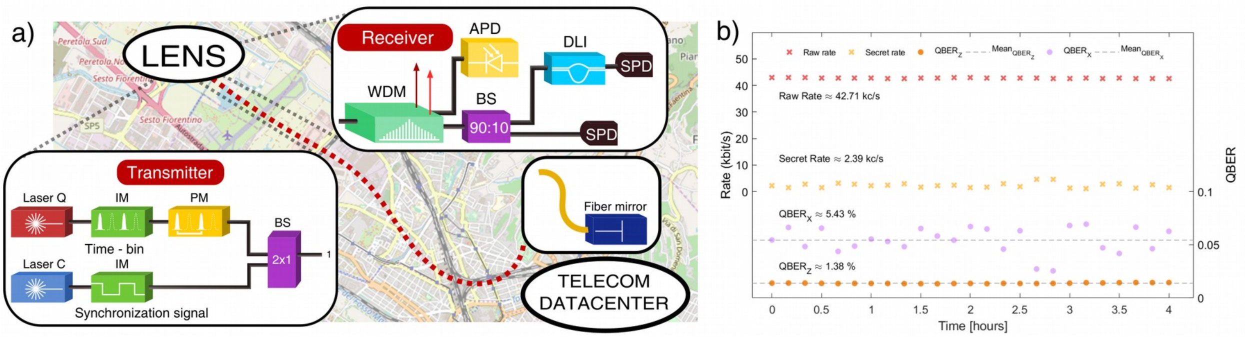

Figure 1 a) Setup of the experiment. The transmitter and the receiver are located at the European laboratory for non- linear spectroscopy (LENS). A fiber mirror, located in a telecom datacenter, allows us to close the loop. **b)** Secret key rate and bit error rate as a function of time. The measurements are continuously acquired without an active stabilization system.

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Beating the Rayleigh limit using two-photon interference

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A promising strategy to determine properties of a composite light source with resolution beating the Rayleigh limit is to measure the emitted radiation in a carefully chosen basis of spatial modes [1]. In contrast to direct imaging, this technique takes advantage of partial spatial coherence of light detected in the image plane, but requires knowledge of certain characteristics of the source, such as its centroid [2]. Such a problem can be viewed from the quantum metrology perspective as a multiparameter estimation task. In general, simultaneous determination of multiple parameters requires implementation of a collective measurement on many copies of the quantum system.

In our recent work [3] we have shown, theoretically and experimentally, that two-photon interference combined with spatially resolved detection of interfered photons provides means to determine simultaneously the centroid and the separation between two point sources avoiding the Rayleigh curse. Using the experimental setup shown schematically in Fig. 1, we determined the separation between the sources with precision better than that achievable with direct imaging, while measuring at the same time the centroid at the Rayleigh limit, as seen in Fig. 2. In the case of non-unit visibility of two-photon interference, equal to 92% in our experiment, recording spatial information was essential to determine the source separation with precision beating the direct imaging limit. The somewhat nontrivial demand of interfering two photons from a realistic classical (thermal) composite source could be satisfied by a construction of a photon number quantum nondemolition (QND) [4] device that heralds, stores, and reroutes incoming photons while preserving their spatial properties [5].

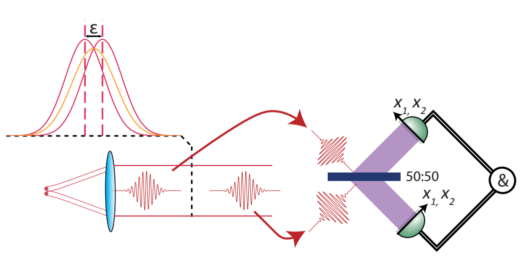

FIG. 1. Two-photon interference scheme for simultaneous determination of the centroid and the separation of two point light sources.

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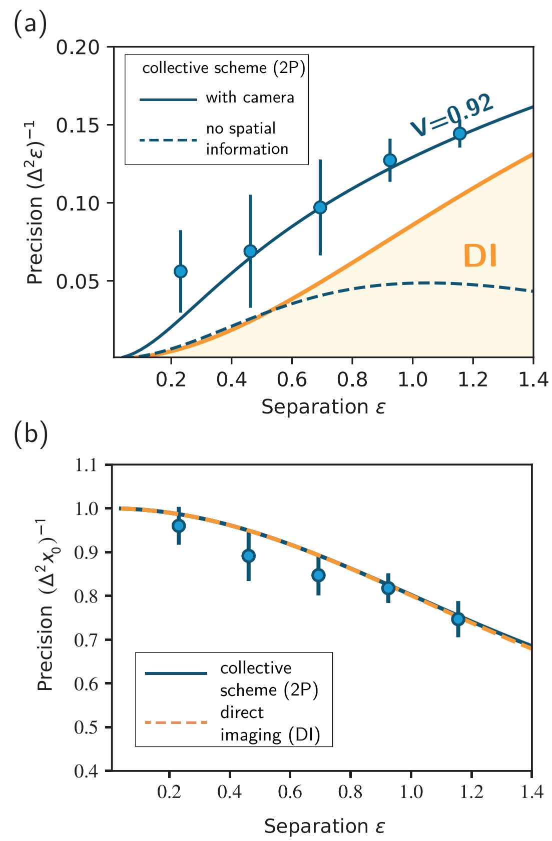

FIG. 2. Precision of (a) the source separation ε and (b) the centroid x_0 measured simultaneously using the two-photon interference setup shown in Fig. 1.

Quantum process tomography with imperfect measurements

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The constant development of new physical quantum processes raises the issue of determining the quality of quantum states preparation and transformations. Many of the modern experiments use the randomized benchmarking technique for this purpose. This approach allows one to estimate the fidelity of quantum gates. However, for the establishing of error correction the quantum process tomography procedure turns out to be more practical as it allows us to completely characterize an unknown quantum transformation, to single out unitary and non-unitary errors and design effective ways for errors correction.

The most of the modern quantum process tomography methods are built on the suggestion of the possibility to prepare ideal quantum states at the gate input and perform ideal quantum measurements at the output, which is not the case in the real experiments. As a result, the process matrix that one obtains after the gate reconstruction does not adequately describe the transformation under research. In the present work the method of preparation and measurement errors reconstruction is considered. This method is based on the tomography of an “empty” quantum gate, which acts over a zero period of time. The obtained information if being used for the further correction of reconstruction procedure by the fuzzy measurements approach.

The current report is the extension of our previous results, which have shown the significant increase of the quantum process tomography quality both theoretically and in experiments conducted on the IBM quantum processor.

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Simulating Thermodynamics with Photons

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Photons and thermodynamics hardly seem words that go together well. A theory meant to describe heat and work exchange looks rather inappropriate for light quanta, virtually isolated from their environment. Yet, photonics can help fostering concepts and methods in in- formation thermodynamics thanks to the relative ease by which one can mimic interactions through quantum simulation. Here we will discuss recent experiments carried out by our groups, illustrating concepts in information thermodynamics by simulating the thermalisation of quantum bits, hence following the transient behaviour of the qubits at finite time.

All our simulations have been performed by means of a photonic quantum gate: by coupling a single qubit, encoded in the polarisation of a photon, to a second ancillary photon, we are able to replicate the quantum state that would be obtained following thermal contact with a reservoir: we can either directly access its observables, or reconstruct it in full by means of state tomography.

First, we will discuss how quantum theory is able to extend this result for open systems by inspecting the trajectory of the density matrix on its manifold. Indeed, this approach can provide an upper and lower bound to the irreversible entropy production, and gives insights on how the information on the initial state is forgotten through a thermalization process [1].

This problem epitomises the simplest tool to measure the temperature of thermal baths with reduced invasivity. At thermal equilibrium, the temperature uncertainty is linked to the heat capacity of the qubit, however, the best precision is achieved outside the equilibrium condition. We will discuss how we have generalised this relation in the nonequilibrium regime, accounting for quantum ef- fects such as coherence [2].

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Non-destructive measurement of superconducting qubit states by Josephson bifurcation oscillator

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A model of non-destructive measurement of Josephson qubit states using a nonlinear bifurcation oscillator was investigated in this paper. The calculations used the method of quantum trajectories (quantum Monte Carlo [1, 2]), which allowed us to study the process of non-destructive measurement of the qubit states in a single realizations, and the average for Rabi-pulses of different duration.

The study of recording and reading information mesoscopic measuring device for two basic states of qubits (calibration of the measuring oscillator). As a result, the influence of signal and noise parameters on the measured value – the number of photons (population levels) of the oscillator. Resonance hysteresis curves for the ground and excited qubit levels are obtained. The optimal range of operating parameters is found, and a method for measuring qubit states during scanning by current (external field amplitude) is demonstrated, which is similar to that presented in [3].

On the basis of the qubit-measuring oscillator model, a method of time monitoring of qubit states is proposed. The possibility of measuring the qubit states by a bifurcation oscillator is demonstrated. It is shown that for a given pulse duration of recording it is possible to determine the relative value of the influence of the measuring device operating in mesoscopic mode on the state of the quantum system (the effect of back-action). In particular, for π-pulse recording, measurements such as “single-shot” can be made, where individual quantum jumps can be seen. For the averaged dynamics of the system on the basis of statistical data, the evolution of the distribution density of the average energy of the oscillator is studied, which shows the probability of finding a qubit in a particular base state.

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Spin properties and quantum control of group-IV vacancy centers in diamond

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Color centers in diamond, i.e. atomic-scale, optically active defects in the diamond lattice, have received large recent attention as versatile tools for solid-state-based quantum technologies ranging from quantum information processing to quantum-enhanced sensing and metrology. They provide individually addressable spins with very long coherence times, narrow optical spectra and bright single-photon emission. However, identifying a spin impurity which combines all of these favorable properties still remains a challenge.

I will present the example of the Silicon vacancy (SiV) center [1] which allows for optical addressing [2] and ultrafast all-optical coherent manipulation [3,4] of its orbital and spin states. The potential of coherent control further extends to dense ensembles of SiV centers, enabling coherent population transfer and strong light-matter interaction via four-wave mixing [5]. However, the SiV center reaches long spin coherence times only in the limit of very low temperatures (<100mK) due to phonon-induced decoherence processes [4,6]. A potential resort are vacancy defects with a heavier group-IV impurity atom, such as GeV, SnV and PbV centers, featuring a larger ground state splitting and thus less susceptibility to phonon-induced decoherence. Here, I will report on spectroscopy of SnV centers which show promising optical and single-photon emission properties.

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Delocalized photon addition for entangling macroscopic light states

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Entanglement is a distinctive feature of quantum mechanics marking the most striking deviations of its predictions from those of classical physics. Although entanglement has been widely experimentally demonstrated in several microscopic systems, entangling larger and larger objects is an increasingly difficult task [1].

Differently from recent optical experiments that demonstrated the generation of a so-called 'micro- macro' entanglement (where one part of a system in a microscopic superposition of vacuum and one-photon states is entangled with another part containing a macroscopic mean number of photons) [2, 3], here we show how to entangle two states, both made of an arbitrarily large number of photons. This 'macro-macro' entanglement is independent of the size of the entangled partners and particularly robust against losses.

Our basic ingredient is the possibility of performing the coherent delocalized addition of a single photon over different modes. In general, the amount of entanglement produced by a balanced superposition of photon creation operators over distinct modes depends on the states of light already present in the two modes before the operation. If both are originally in a vacuum state, one obtains a single-photon mode-entangled state [4]. If a vacuum and a coherent state populate the two input modes, a so-called hybrid discrete/continuous-variable entanglement is generated [5].

Here, by studying the effect of delocalized single-photon addition on two input modes containing identical coherent states, we experimentally verify their entanglement for mean photon numbers up to about 60 [6]. Discorrelation [7], a new joint statistical property of multimode quantum states, is also experimentally demonstrated here for the first time.

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Quantum fluctuation approach to Josephson junctions

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The quantum features of Josephson circuits are usually studied by describing these systems as non-linear quantum oscillators. It will be discussed how and when such phenomenological approaches can be derived within the BCS theory by considering sums of microscopic degrees of freedom that scale differently from the standard mean-field quantities.

Computational Complexity and the Nature of Quantum Mechanics

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Quantum theory (QT) is one of the most fundamental, and accurate, mathematical descriptions of our physical world. In spite of nearly one century passed by since its inception, we do not have a clear understanding of such a theory yet. In particular, we cannot really grasp the meaning of the theory: why it is the way it is.

This paper aims at finally explaining QT while giving a unified reason for its many paradoxes. We pursue this goal by having QT follow from two main principles:

Coherence: The theory should be logically consistent.

Computation: Inferences in the theory should be computable in polynomial time.

The first principle is what we essentially require to each well-founded mathematical theory, be it physical or not. The second principle will turn out to be central. It assumes that there should be an efficient way to execute the theory in a computer.

QT is an abstract theory that can be studied detached from its physical applications. For this reason, people often wonder which part of QT actually pertains to physics. In our representation, the answer to this question shows itself naturally: the computation principle defines the physical component of the theory.

Let us recall that QT is widely regarded as a ``generalised" theory of probability. In this work we make the adjective ``generalised" precise. In fact, our coherence principle leads to a theory of probability, in the sense that it disallows ``Dutch books": this means, in gambling terms, that a bettor on a quantum experiment cannot be made a sure loser by exploiting inconsistencies in their probabilistic assessments. But probabilistic inference is in general NP-hard. By imposing the additional principle of computation, the theory becomes one of ``computational rationality": one that is self-consistent (or coherent), up to the degree that polynomial computation allows. This weaker, and hence more general, theory of probability is QT.

As a result, for a subject living inside QT, all is coherent. For us, living in the classical probabilistic world (not restricted by the computation principle), QT displays some inconsistencies: precisely those that cannot be fixed in polynomial time. All quantum paradoxes, and entanglement in particular, arise from the clash of these two world views: i.e., from trying to reconcile a full theory (i.e., classical physics) with a theory of computational rationality (QT). Or, in other words, from regarding physics as fundamental rather than computation.

But there is more to it. We show that the theory is ``generalised" also in another direction, as QT turns out to be a theory of ``imprecise" probability: in fact, requiring the computation principle is similar to defining a probabilistic model using only a finite number of moments; and therefore, implicitly, to defining the model as the set of all probabilities compatible with the given moments. In QT, some of these compatible probabilities can actually be signed, that is, they allow for ``negative probabilities". In our setting, these have no meaning per se, they are just a mathematical consequence of polynomially bounded coherence (or rationality).

Single quantum gates and Bell's states using the controlled adiabatic evolutions

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Fundamental quantum gates can be implemented effectively using adiabatic quantum computation or circuit model. Recently, Itay Hen combined the two approaches to introduce a new model called controlled adiabatic evolutions [Phys. Rev. A, 022309 (2015)]. This model was specifically designed to implement one and two-qubit controlled gates. Later, Santos extended Hen's work to implement n-qubit controlled gates [Sci. Rep., 15775 (2015)]. In this study, we demonstrate the possibility of preparing Bell's states using the controlled adiabatic evolutions approach, as well we discuss the fidelity results of implementing single quantum gates and Bell's states using the controlled adiabatic evolutions in open systems.

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Berge Englert

Evidence in quantum data

The data acquired in quantum experiments are unavoidably affected by statistical fluctuations and, therefore, the interpretation of the data must rely on methods from statistics. While p-values and confidence intervals are routinely reported, this practice is questionable.

Bayesian concepts, instead, fit quite naturally to quantum data. This talk deals with various aspects of Bayesian methodology, in particular with the Bayesian notion of what constitutes evidence in favor of, or against, a hypothesis.

Sequential measurements: optimally getting around the collapse postulate and the no-broadcasting theorem

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In a recent paper [1], a scheme was proposed where subsequent observers can extract unambiguous information out the initial state of a qubit. In the scheme, Alice prepares a qubit in one of two possible states. The qubit is sent to Bob, who performs a measurement on it and, then, sends it on to Charlie, who can also perform a measurement on it. The goal for Bob and Charlie is to determine the state prepared by Alice without making an error. When the states are non-orthogonal, this cannot be accomplished with 100% success rate. Besides the conclusive outcomes, identifying the states unambiguously, Bob's and Charlie's measurements must be allowed to have an inconclusive outcome (failure). When they find the failure outcome, they don't make any conclusion about the initial state and hence do not make an error. In the original paper, the optimum joint probability of success was derived for the case when the two states were prepared with equal probability. In this paper, we generalize the problem for arbitrary preparation probabilities (arbitrary priors). We discuss two different schemes: one where, in addition, the joint probability of failure is also minimized, and another, without minimizing the joint probability of failure. We also calculate the mutual information for these schemes and show that there are some parameter regions for the scheme without minimizing the joint failure probability where, even though the joint success probability is maximum, no information is actually transmitted by Alice. Finally, we also discuss a scheme where errors are allowed and minimize the joint probability of both Bob and Charlie erroneously identifying the input.

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High sensitivity magnetic measurements with Nitrogen Vacancy Centers in Diamond

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Nitrogen Vacancy centers magnetometry is based on the measurement of the shift of the magnetic resonance due to the Zeeman effect. The transition between triplet spin states of the electronic ground state of the Nitrogen-Vacancy center can be controlled by a magnetic field oscillating at microwave frequencies. When illuminated by a green light, a NV in the state with ms=+-1 shows a lower photoluminescence (PL) rate compared to the one in ms=0 state, due to the presence of a non radiative decaying channel in the former case. Starting from a NV initialised in the state ms=0, a magnetic field oscillating at the frequency associated to the energy difference between spin states will results in equal population of the two levels and hence in a decrease of PL rate. This is the basic mechanism of Continuos Wave Magnetometry with NV centers.

In lock-in magnetometry with NV centers the microwave is frequency modulated and the oscillating fluorescence is detected using a photodiode and a lock-in amplifier. This technique shift the detection of the fluorescence to frequency in the orders of tens of kilohertz where the electromagnetic noise is lower.

Magnetic measurements obtained in Quantum Optics lab at INRIM using a sample with shallow NV's are shown.

Femtosecond Laser Writing: A powerful tool for Integrated Diamond Quantum Photonics

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Diamond has outstanding properties of optical transparency, hardness, bio-inertness and thermal conductivity. Recently, it has interested the scientific community due to a naturally occurring defect, the Nitrogen Vacancy (NV) color center which has been an ideal candidate as a qubit with long electron spin coherence times and its ability to be found, manipulated and read out optically (1). The spin states can be used for sensing magnetic and electric fields through the Zeeman and Stark effects, respectively and hence pose as powerful atom sized field sensors.

Recently, ultrafast laser writing has been shown as a versatile tool for integrated photonics in diamond (2-4). In this work, we will describe how laser writing can be used for inscribing optical waveguides, Bragg gratings, high aspect ratio microchannels and to deterministically inscribe NV centers in the bulk of diamond. For field sensing applications, ensemble NVs will play key role allowing higher sensitivities of detection. We also describe laser writing of ensemble NVs in high nitrogen content diamond, grown through high-pressure-high-temperature (HPHT) technique. The waveguide inscription itself produced high density of NVs. The NV density was estimated to be about 1.1×10^{15} based on the power dependence of photoluminescence saturation suggesting the possibility of a device with state-of-the-art magnetic and electric field sensitivities. We will discuss ways to further improve these sensitivities and integrate with other laser written elements for fully integrated lab on chip devices.

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Higher Order Quantum Computation and Quantum Causal Structures

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The most general (probabilistic) transformation of a quantum state is described by a quantum operation. Quantum operations can be axiomatically defined as the most general map which are compatible with the probabilistic structure of the theory, and produce a legitimate output when applied locally on one side of a bipartite input. These admissibility requirements characterise quantum operations as completely positive trace non increasing linear map. What happens if we now consider maps from quantum operations to quantum operations? Can we give an axiomatic characterisation of these objects according to some generalised notion of admissibility? What happens if we recursively iterate the construction and we define a full hierarchy of higher order maps?

Some special cases of higher order maps have been already studied in the literature. Quantum Networks, which encompass all conceivable quantum protocols, form a sub-hierarchy of maps which are endowed with a well ordered causal structure and they can be realised as quantum circuits. However, more general higher order maps may exhibit an indefinite causal structure which prevent a physical implementation as a quantum circuit. Non circuital higher order maps allow to accomplishing certain tasks that cannot be achieved by circuital maps, like the violation of causal inequalities, and can outperform circuital maps in certain quantum information processing tasks. The experimental realisation of non-circuital higher order maps has also been considered.

Notwithstanding many results on the subject, a general mathematical framework is still missing. The aim of this contribution is to fill this critical gap by providing an axiomatic framework for higher order computation. Higher order quantum computation is introduced axiomatically with a formulation based on the language of types of transformations. Complete positivity of higher order maps is derived from the general admissibility conditions instead of being postulated as in previous approaches We will see that a complete mathematical characterisation of admissible maps is possible and that the set of admissible maps of a given type is in correspondence with a convex subset of the cone of positive operators. This result encompasses the analysis existing in the literature and gives them an axiomatic operational foundation. The present axioms for higher order computation have a purely operational nature and do not rely on the specific mathematical structure of quantum theory. Therefore, our framework can be applied to general operational probabilistic theories.

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Lorentz boosts of bispinor Bell-like states

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We describe in this paper the e ects of Lorentz boost on the quantum entanglement encoded in two-particle Dirac bispinor Bell-like states. Each particle composing the system described in this formalism has three degrees of freedom: spin, chirality, and momentum, and the joint state can be interpreted as a 6 qubit state. Given the transformation law of bispinor under boosts, we compute the change of the Meyer-Wallach global measure of quantum entanglement due to the frame transformation and study its equivalence to the results obtained for the relativistic spin 1/2 Bell-like states, constructed in the framework of the irreducible representations of the Lorentz group. We verify that the monotonic increase of the global entanglement under boosts for ultra relativistic states is solely due to an increasing of the entanglement associated with the spins subsystems. For such ultra relativistic states, the entanglement related to the chirality degrees of freedom is invariant, and the variation of the global entanglement of bispinor states are the same as the one calculated for relativistic spin 1/2 states. We also show that the particle-particle entanglement is invariant under boosts for any Bell-like state.

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Tomography of Quantum-States with Photon-Number-Resolving Homodyne Detection

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Quantum optical states are usually reconstructed by means of optical homodyne tomography [1] based on homodyne detection. In standard homodyne detection, the optical signal interferes at a balanced beam splitter with a high-intensity coherent state, the local oscillator (LO). The two outputs of the beam splitter are detected by two pin photodiodes, whose difference photocurrent is amplified, divided by the value of the LO amplitude and recorded as a function of the LO phase. This procedure is a measure of the signal-field quadrature and can be used to retrieve the complete information on the state.

As an alternative, a homodyne-like (HL) detection scheme can be used, in which the intensity of the LO is decreased and photon-number-resolving (PNR) detectors replace the photodiodes. HL detection has been successfully exploited for a state-discrimination protocol with coherent states [2,3] and suggested to outperform standard homodyne detection in quantum key distribution with continuous variables [4]

Here we demonstrate it is also possible to perform quantum tomography of CV systems using the HL detection scheme [5]. In particular, the HL scheme may be efficiently employed to reconstruct the density matrix of single-mode quantum states, and to compute the expectation values of the first moments of the quadrature operator.

We have tested the HL scheme on a number of quantum states, using experimental data (coherent and phase-averaged coherent states) and simulated data (Fock states) [6]. Our results demonstrate that a highly intense LO is not necessary to perform homodyne detection: even a modest unbalancing between signal and LO is sufficient to successfully perform quantum-state tomography.

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Pulsed-Wave Transmission Spectroscopy of Spin Ensembles Through Planar Superconducting Microwave Resonators

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Encoding quantum bits as well as performing any kind of quantum information processing requires the development of protocols for the initialization, the manipulation and the reading of quantum states. We have recently developed superconducting YBCO planar resonators working at microwave frequencies to perform transmission spectroscopy on molecular spin ensembles at low temperatures [1,2]. Planar resonators are robust and scalable resonant geometries which allow to couple to ensembles of magnetic spin impurities and also offer an easy way to addressing them through sequences of microwave pulses. Along this line, we are currently developing a set-up for the realization of pulsed-wave transmission spectroscopy at low temperatures to test the viability of qubit encoding. Here, the synthesis of the microwave pulses is done with an Arbitrary Waveform Generator, while the superconducting resonant geometry is used to drive the evolution of the spins under the desired pulse sequence. In this work, we first focus on the behavior of our empty YBCO resonators under single driving pulses. We then present our preliminary results concerning the manipulation of molecular spin ensembles of Vanadyl Phthalocyanines and of Organic Radicals [3]. More specifically, we focus on the measure of the phase memory time with standard Hahn echo sequences [3].

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Separated Schmidt modes in angular spectrum of biphotons

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We prepare angular multimode biphoton states (so-called qudits) by means of pump angular spectrum modulation. The modes are prepared in the Schmidt basis which allows one to get rid of detection losses. The pump is modulated with the help of a spatial light modulator instead of slits [1] which gives more flexibility in choosing the specific biphoton angular shape.

We show experimental results for a given biphoton spatial distribution shape of several gaussian peaks with a gaussian envelope.

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Nonclassicality with Mesoscopic Levitated Objects

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Mesoscopic objects of 10^{-17} kg to 10^{-14} kg can now be trapped, controlled and released from traps. We will describe various theoretical schemes to explore their nonclassical behaviour and highlight how the non-classical behaviour of gravity can also be explored by witnessing their entanglement.

Finally, I will discuss one of the simplest schemes possible to check for the nonclassicality of a mesoscopic object in a coherent or thermal state in a trap, namely through successive spatial measurements leading to the violation of macroscopic realism as witnessed by the Leggett-Garg inequality.

Integrated single photon sources with colloidal semiconductor nanocrystals

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Core/shell colloidal semiconductor nanocrystals are very efficient room temperature single photon emitters. In particular, in asymmetric core/shell nanoparticles (dots-in rods) with a spherical CdSe core surrounded by a rod-like CdS shell, blinking effects, multi-excitonic emission and polarization of the emitted photons can be independently controlled by tuning the shell dimensions [1]. This allows an unprecedented capability in radiative channels engineering, making dot-in-rods “state of the art” blinking-free sources of polarized single photons on-demand.

In this talk I will discuss our recent results and the different strategies we are pursuing to develop hybrid photonic devices by coupling single nanocrystals with photonic structures such as deep parabolic mirrors [2], liquid crystals [3], semiconductor nanowires [4] and tapered nanofibers. In particular the deposition of a single emitter on a nanofiber and the observation of single photon statistics through the guided mode of the fiber will be reported. Finally I will show how this hybrid system is a very promising playground for novel chiral optics experiments, including a spin-orbit coupling effect for light [5].

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Fundamental limits in detecting localisation effects

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Advances in the control of quantum mechanical systems have seen experiments place larger objects in quantum mechanical states. Yet quantum correlations are absent from the classical physics which emerges at the macroscopic scale. Collapse models propose a non-deterministic mechanism which suppress quantum effects in macroscopic objects while having negligible impact on microscopic systems [1]. Localisation of a test particle due to collapse models causes additional spreading of the particle's wavefunction. We explore the attainable precision for such localisation rates when a free particle is allowed to evolve, with particular focus around the parameters of the proposed MAQRO mission [2]. As well as the preparation of thermal states we consider the potential impact of generating mechanical squeezing.

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Excess of a Matrix and Bell Inequalities

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We recall the standard definition of the excess of a Hadamard matrix and propose generalizations of this notion. A connection between the notion of the excess of a matrix and Bell inequalities (CHSH) is provided. We characterize infinitely many bipartite Bell inequalities in every scenario solely by applying basic matrix theory to the matrix induced by the Bell operator. In particular, we show that any regular matrix (with a fixed sum of entries in each row and column) implies a bipartite Bell inequality with no quantum advantage, regardless on the number of settings and outcomes. We present two exemplary applications: a tight trade-off relation between quantum non-locality and contextuality for any bipartite Bell inequality in any scenario and calculation of the zero—error Shannon capacity of a channel related to a family of weighted confusability graphs with an arbitrary number of vertices.

[joint work with D.Goyeneche (Antofagasta), D.Alsina (Leeds) and O.Turek (Ostrava)]

Generating GHZ states with squeezing and post-selection

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(Dated: March 22, 2019)

The emergence of quantum computing, quantum information processing and quantum sensing as rapidly developing areas of research in both academia and industry, relies principally on quantum phenomena such as superposition and entanglement. These phenomena allow the development of quantum computational technology which overcome limits set by its classical counterpart in computational speed of complex algorithms. In particular, quantum sensors, devices which utilize quantum correlations to improve sensitivity of measurement, demonstrates the potential of quantum-enhanced technology [1]. Examples include applications in atomic clocks and magnetic field and radio detection (see [2–5]).

To this end, it becomes paramount to develop a well-defined protocol to produce and further exercise control over states of quantum bits which exhibit desired quantum mechanical traits. The same control protocols can be employed to produce quantum correlations that suppress phase noise in multiparticle quantum interference, metrology experiments [6–8]. Essentially, our investigation focuses on establishing a protocol which uses quantum control operations combined with measurement post-selection with the aim of producing highly entangled metrologically relevant states (see [9, 10] for relevant discussions on measures of multipartite entanglement). We further study the optimal parameters required to produce a maximal fidelity overlap of this state, denoted as the *Projected Squeezed* state (or PS state), with the well-known *Greenberger-Horne-Zeilinger* state (commonly referred to as the maximally entangled state or GHZ state, see [11]).

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Generating GHZ states with squeezing and post-selection

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The emergence of quantum computing, quantum information processing and quantum sensing as rapidly developing areas of research in both academia and industry, relies principally on quantum phenomena such as superposition and entanglement. These phenomena allow the development of quantum computational technology which overcome limits set by its classical counterpart in computational speed of complex algorithms. In particular, quantum sensors, devices which utilize quantum correlations to improve sensitivity of measurement, demonstrates the potential of quantumenhanced technology [1]. Examples include applications in atomic clocks and magnetic field and radio detection (see [2–5]).

To this end, it becomes paramount to develop a well-defined protocol to produce and further exercise control over states of quantum bits which exhibit desired quantum mechanical traits. The same control protocols can be employed to produce quantum correlations that suppress phase noise in multiparticle quantum interference, metrology experiments [6–8]. Essentially, our investigation focuses on establishing a protocol which uses quantum control operations combined with measurement post-selection with the aim of producing highly entangled metrologically relevant states (see [9, 10] for relevant discussions on measures of multipartite entanglement). We further study the optimal parameters required to produce a maximal fidelity overlap of this state, denoted as the Projected Squeezed state (or P S state), with the well-known Greenberger-Horne-Zeilinger state (commonly referred to as the maximally entangled state or GHZ state, see [11]).

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The world's fattest Schroedinger cat

Tommaso Calarco

Quantum optimal control enables the creation of highly non-classical states both for technological applications and for fundamental physics purposes. Our recently developed Remote dressed chopped random basis method (RedCRAB) enables remote optimization of experiments as a cloud-based service. I will report the creation of a 20-qubit GHZ state (the largest to date) enables by our method.

Increased creation efficiency of nitrogen-vacancy centres in diamond by electron beam irradiation at high temperature

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The nitrogen-vacancy (NV) centre is a fluorescent defect in the diamond lattice used for quantum sensing applications. In the past decade, researchers developed sensing applications such as sub-picotesla magnetometry [1], nuclear magnetic resonance [2] and microwave structure characterisation [3] where the sensitivity was enhanced using high density of NV centres in the diamond lattice. The advantage of ensemble-based sensing consists in the simultaneous acquisition of the signal from a large number of NV centres (behaving as multiple independent sensors) and therefore improving the measured sensitivity and signal-to-noise ratio[4]. As such, the density of NV centres is an important parameter to increase to potentially further enhance the sensitivity of all ensemble-based techniques.

In this study [5], we processed nitrogen-rich high-pressure high-temperature diamonds using high-temperature electron beam irradiation (referred as "annealing *in situ*") to create samples with a high density of NV centres. We estimated the creation efficiency of the NV centres from the concentration of initial substitutional nitrogen and the density of NV centre created by the processing technique, calculated using both infrared and visible spectroscopy. Our measurements show that with the annealing *in situ* process we can increase the creation efficiency of NV centres to approximately double the value obtained with the commonly used reference technique, where the irradiation and annealing steps were carried out consecutively.

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The Fundamental Connections Between Classical Hamiltonian Mechanics, Quantum Mechanics and Information Entropy

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In a recent paper [1] we have shown that classical and quantum Hamiltonian particle mechanics can be rederived from a handful of physical assumptions. We will present and expand a consequence of that work, namely that classical Hamiltonian mechanics coincides with conservation of information entropy, and how this insight allows us to better understand quantum mechanics as well.

We will start by showing that classical Hamiltonian mechanics can be recovered from two fundamental assumptions. The first is that the system we study is infinitesimally reducible: it is made of infinitesimal parts and the state of those parts is equivalent to the state of the whole system. The state of the overall system is then a distribution over the states of the infinitesimal parts. As states must be defined independently of coordinate system (i.e. of observer), the density over the states of the parts must be invariant under coordinate transformation. This allows us to recover the geometrical structure of phase space (i.e. state variables organized in conjugate pairs). The second assumption is that of deterministic and reversible evolution: knowing the state at one time is enough to predict the state at future times and reconstruct the state at past times. This means that the density for a given state will be mapped exactly to a future state, which will give us Hamiltonian evolution. We then show that requiring densities to be coordinate invariant and not change in time is equivalent to requiring that the information entropy (i.e. the number bits of identify an element of the distribution up to unit precision) is conserved.

Throughout the derivation, we will see how classical analogues of quantum mechanics (i.e. wave number, uncertainty principle, particle/anti-particle states) naturally emerge. We will discuss how quantum mechanics differs from classical mechanics by assuming irreducibility instead: that the system is still made of infinitesimal parts but that the state of the overall system tells us nothing about the state of the parts. We will see how this qualitatively leads to the known quantum effects.

This work is part of a larger project [2] that aims to rederive the known laws of physics from a handful of physical assumptions.

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Topological phenomena in one-dimensional quantum walks of structured light

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Quantum walks (QWs) represent a broad class of quantum dynamics that have proved extremely useful in different scenarios, ranging from quantum computation to the simulation of transport phenomena and topological phases. They have been already implemented in a variety of experimental platforms, mostly in their 1-dimensional (1D) version. Relying on a photonic platform where the walk takes place in the space of optical modes carrying orbital angular momentum [1], we study 1D quantum walks exhibiting the topological phases of Floquet systems featuring chiral symmetry [2, 3], in analogy to the prototypical SSH model describing electronic transport in a poly-acetylene chain [4]. In such models, the invariants are associated with the winding number of the eigenstates, forming the energy bands of the system. These phases of matter are typically investigated through the analysis of protected edges states. Following a different approach, here we instead focus our attention on bulk observables. In particular, we find that important information about the system topology can be extracted from the statistical moments associated with photons OAM spectrum [2]; quite remarkably, specific combinations of such moments are quantised and proportional to the topological invariants [3], hence can be used to detect topological phases. Such quantization arises in absence of any external force, and it is robust to perturbations that preserve the system symmetries. We confirm experimentally these results in our photonic platform, and report the measurement of complete topological invariants characterizing this class of systems [3, 5]. We demonstrate that the method we propose is widely applicable in a variety of different 1D topological systems, including walks characterized by high-dimensional coin states [6], and readily implementable in experimental platforms that are presently used to simulate these exotic phases.

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Classical imaging with undetected light

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In a recent work, Lemos et al. constructed the intensity and phase images of an object by detecting photons which have never interacted with it [1]. The authors used the pairs of entangled photons generated by spontaneous parametric down conversion as a quantum source, such that one of the photons could interact with the object while the other one was detected. The quantum correlations between the photons and a fundamental path indistinguishability in an interferometer were responsible for that result.

We obtained the phase and intensity images of an object by detecting classical light which never interacted with it [2]. With a double passage of a pump and a signal beams through a nonlinear crystal, an idler beam is produced by stimulated parametric down conversion in an interferometric way. The detection of the idler beam reveals the amplitude and phase patterns of an object that was in the path of the signal beam. The frequencies of the signal and idler beams are different, what can result in promising applications of the technique in situations where the light that interacts with the object has a wavelength for which detectors are not available.

We showed therefore that the method used in [1], where quantum images of objects were produced by detecting photons that did not interact with it, has a classical analog. As in the case of the entangled states produced in [1], classical states of light produced by stimulated parametric down conversion also have a high degree of spatial and phase correlations. We have used these correlations to achieve our results. The truly quantum aspect of the experiment of Lemos et al. is that high quality images were produced without stimulated emission, which cannot be explained by classical physics.

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Noise-robust quantum sensing via optimal multi-probe spectroscopy

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The dynamics of quantum systems are unavoidably influenced by their environment, but in turn observing a quantum system (probe) can allow one to measure its environment.

Measurements and controlled manipulation of the probe such as dynamical decoupling sequences as an extension of the Ramsey interference measurement allow to spectrally resolve a noise field coupled to the probe.

Here, we introduce fast and robust estimation strategies for the characterization of the spectral properties of classical and quantum dephasing environments.

These strategies are based on filter function orthogonalization, optimal control filters maximizing the relevant Fisher Information and multi-qubit entanglement.

We investigate and quantify the robustness of the schemes under different types of noise such as finite-precision measurements, dephasing of the probe, spectral leakage and slow temporal fluctuations of the spectrum.

On the temporally nonlocal character of the quantum computational speedup

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The term *Quantum computational speedup* accounts for the fact that solving certain problems can be more efficient quantumly than classically. For example, Bob, the problem setter, hides a ball in a chest of four drawers. Alice, the problem solver, has to find the ball by opening drawers (i.e. by *querying the oracle*: is the ball in that drawer?). In the classical case, Alice may need to open up to three drawers, but always one with the quantum search algorithm devised by Grover.

Until now, there is no full, systematic and quantitative explanation of quantum speedup. It is commonly believed that the speedup originates from clever manipulation of coherent superposition states, and in particular, entangled states. The latter customarily represent spatial nonlocality, but there is a viable possibility that temporal nonlocality [1,2] is present and influential as well. With respect to Grover's algorithm, temporal nonlocality can be investigated using the following scheme.

The usual representation of quantum algorithms is limited to the process of solving the problem. It omits the process of setting the problem and, within it, the initial measurement, i.e. the preselection. Similarly, the postselected state usually does not have a fundamental role. Of course, in order to see nonlocality, one needs a complete representation of the quantum process.

Our first step is thus completing the representation [3-5]. By the initial measurement, Bob selects a problem setting at random out of a mixture thereof (he could unitarily change it into a desired setting). Then Alice, by oracle queries and other unitary transformations, computes the corresponding solution and reads it by the final measurement. With probability one of reading the solution, there is a unitary transformation between the initial and final measurement outcomes. This process is identical to the preselection-unitary evolution-postselection structure known from the Two-State Vector Formalism (TSVF) [6], and thus we would like to borrow the tools developed there [7-10] for the analysis of quantum speedup.

There is an immediate consequence. The extended representation works for Bob and any external observer, not for Alice. It would tell her the problem setting selected by Bob and thus the solution of the problem (e.g., both the number of the drawer with the ball) before she computes it. We must shield Alice from the problem setting by postponing at the end of the unitary part of her action the projection of the quantum state associated with the initial measurement [7]. The fact that this only works halfway supports a temporally nonlocal explanation of the speedup with no causality violations.

Because of the reversibility of the process between the initial and final measurement outcomes, we should assume that the initial and final measurements contribute to the selection of the problem setting and thus the solution in a time-symmetric way (again suggesting full agreement with the TSVF). The half information selected by the initial measurement propagates forward in time until becoming part of the outcome of the final measurement, the half selected by the final measurement backwards in time until becoming part of the outcome of the initial measurement. Of course, once the problem setting has been selected one way or another, nothing changes for the quantum algorithm, in particular the number of queries required to reach the solution.

Postponing the initial projection of the quantum state shields Alice from the half information coming to her from the initial measurement, not from the half coming to her back in time from the final measurement. All is as if, before beginning her problem-solving action, Alice knew in advance half of the information about the solution of the problem she will read in the future. The computational complexity of the problem to be solved by her is correspondingly reduced [3-5]. It turns out that the number of queries required to solve any oracle problem in an optimal quantum way is that of a classical algorithm that knows in advance half of the information about the solution [3-5].

Taking the superposition of all the time-symmetrized algorithms, for all the possible ways of equally sharing the selection of the information between the initial and final measurements, rebuilds the extended quantum algorithm (up to postponing the initial projection of the quantum state at the end of the unitary part). The present temporally nonlocal account of the speedup would thus be a mathematically legitimate interpretation of the extended representation of quantum algorithms. The physical meaning of this mathematical possibility is discussed.

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History operators in quantum mechanics

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We propose to describe a quantum system at all times by means of a “history operator” C, encoding measurements and unitary time evolution between measurements.

These operators naturally arise when computing the probability of measurement sequences, and generalize the “sum over position histories” of the Feynman path-integral.

Probabilities of outcomes are obtained as $Tr(C^{\dagger}P\ C)/Tr(C^{\dagger}C)$, where P is the projector corresponding to the measurement. A similar formula yields probabilities for intermediate measurements, and reproduces the result of the two-vector formalism in the case of given initial and final states.

We apply the history operator formalism to a few examples: entangler circuit, Mach Zehnder interferometer, teleportation circuit, and three-box experiment.

Generation of two- and three-photon states in an ultrathin nonlinear crystal

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The spontaneous generation of three photon states is a major challenge in quantum optics. Although many systems have been investigated, direct three photon generation has not been observed due to the very low efficiency of the process. One of the major issues is to find suitable materials with high nonlinearity that either allow birefringent phase matching or that can be used to build waveguides enabling modal phase matching. Furthermore, intermodal phase matching reduces the efficiency of the process proportionally to the modal overlap. For these reasons we propose to use a thin layer of highly nonlinear material to loosen the phase matching conditions.

It is well known that any parametric process can be realized without phase matching. The efficiency has an oscillatory behavior with the crystal length, with the period given by the coherence length, defined as the inverse of the phase mismatch. In our system we use a 230nm thick layer of silicon on a sapphire substrate. Silicon has a third order nonlinearity 4 orders of magnitude higher than fused silica, which is the benchmark material for fiber-based three-photon generation.

As a first step we tested the generation of spontaneous parametric down conversion in a similar system. We used a 6µm thick layer of x-cut Lithium Niobate (LN) crystal grown over a substrate of fused silica. In this way we are able to use the highest nonlinear component of the susceptibility tensor (d_{33}=40pm/V) when the pump, the signal and the idler photons are polarized along the z-axis. The high nonlinearity partially compensates for the reduced interaction length resulting in measurable coincidence rates. We were also able to fully characterize this source, starting from the second order correlation function, which gave us a clear signature of two photon emission. Furthermore we measured the joint spectral and angular intensity using stimulated emission tomography [1]. This approach gives us a great freedom on the choice of material and leads to a state with a very large bandwidth and a high degree of entanglement.

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Hong-Ou-Mandel effect under partial time reversal: a destructive interference effect in the amplification of light

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In the usual, predictive approach of quantum mechanics, one deals with the preparation of a quantum system followed by its time evolution and ultimately its measurement. In the retrodictive approach of quantum mechanics, one postselects the instances where a particular measurement outcome was observed and considers the probability of the preparation variable conditionally on this measurement outcome. This can be interpreted as if the actually measured state had propagated backwards in time to the preparer. Here, we present an intermediate picture, called "partial time reversal", where a composite system is propagated partly forwards and partly backwards in time. As a striking application, we focus on the simplest two-mode linear-optical component, namely a beam splitter, and show that it transforms into a two-mode squeezer under partial time reversal [1]. More generally, by building on the generating function of the matrix elements of Gaussian unitaries in Fock basis, we prove that their multiphoton transition probabilities obey simple recurrence equations. This method is developed for Gaussian unitaries effecting both passive and active linear coupling between two bosonic modes [2]. The recurrence exhibits an interferometric suppression term which generalizes the Hong-Ou-Mandel effect for more than two indistinguishable photons impinging on a beam splitter of transmittance 1/2. It also exhibits an unexpected 2-photon suppression effect in an optical parametric amplifier of gain 2 originating from the indistinguishability between the input and output photons which we coin "timelike" indistinguishability (it is the partial time-reversed version of the usual "spacelike" indistinguishability which is at work in the Hong-Ou-Mandel effect).

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Optimality of Gaussian and non-Gaussian measurements for Gaussian metrology

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A central issue in quantum metrology is to find an optimal setup to measure a quantity with a precision beyond the standard quantum limit. This is usually assessed by the ability to reach the lower bound of the estimation error given an input state and a parameter-encoding process. Useful optical resources for metrology are Gaussian states and Gaussian measurements, both being experimentally available in a well-controlled and reliable manner. Questions of practical relevance and fundamental interest arise in context. Can Gaussian measurements achieve the ultimate bound in single-mode Gaussian metrology? If yes, what are the optimal Gaussian measurements setups? If no, what kind of non-Gaussian measurements are required and how can they be implemented in practice?

In this work, we identify three types of optimal Gaussian measurement setups yielding the maximal Fisher information depending on the type of probe state in single-mode Gaussian phase estimation. The homodyne measurement is shown to attain the ultimate bound for both displaced thermal probe states and squeezed vacuum probe states. For other Gaussian probe states, the optimized Gaussian measurements are not optimal although sometimes nearly optimal. For the latter, we demonstrate that the non-Gaussian measurement on the basis of the product quadrature operators $\hat{X}\hat{P}+\hat{P}\hat{X}$ is required for full optimality. We also prove the equivalence of optimal measurements between quantum Fisher information and quantum fidelity, enabling much simpler derivations to optimal positive-operator-valued-measurements for Gaussian metrology.

Experimental implementation of the above optimal non-Gaussian measurements seems quite challenging within current technology although they are in principle physical observables. Alternatively, we employ particular non-Gaussian measurements using the projection synthesis technique, where a set of projectors can be optimized by engineering an ancillary quantum state. We find that the optimized projectors lead to a larger Fisher information than those obtained by the optimal Gaussian measurements. To our knowledge, this is the first time when the projection synthesis is employed for quantum metrology. We thus expect this work will pave the way for various scenarios where optimal measurements are unknown.

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Nonlinear optics with bright squeezed vacuum: high efficiencies, rogue waves, and Pareto photon distribution

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Bright squeezed vacuum (BSV), the radiation at the output of a strongly pumped unseeded parametric amplifier, is known to have strong and fast intensity fluctuations. This makes it more efficient than coherent light for pumping multiphoton effects. Recently we have demonstrated this feature for non-phasematched 2nd-4th harmonic generation [1]. In particular, for the 4 th harmonic generation, BSV is two orders of magnitude more efficient than coherent light with the same pulse duration and energy per pulse. The resulting radiation of optical harmonics has even stronger intensity fluctuations than BSV and manifest giant superbunching. Their photon-number distributions are heavy-tailed and resemble the statistics of 'rogue waves' in the ocean nd their analogues in nonlinear optics.

For optical supercontinuum generated from BSV, we observe even more drastic 'rogue-ave' behaviour, featuring a power-law (Pareto-type) probability distribution of photon number [2]. The power exponent of this distribution is less than two, meaning that even the mean photon number is indefinite, to say nothing of higher moments. The highest bunching parameter we observed was 170, but its value is, in principle, unlimited because the second moment of the photon number diverges.

This extreme superbunching has interesting consequences for photon subtraction experiments, which we indeed performed with supercontinuum produced from BSV. As a result of photon subtraction, the mean photon number increased by two orders of agnitude. From the viewpoint of quantum thermodynamics, this means that a large amount of thermodynamical work can be extracted from this state of light.

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Quantifying nonclassicality and qualifying photodetectors through autocorrelation functions

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Glauber's autocorrelation functions [1] are a powerful and versatile tool for the characterization of light statistics, which are being extensively used in quantum optics experiments.

Here we employ the second-order autocorrelation function in both the characterization of nonclassical states of light and the estimation of the spurious effects of detectors [2]. In particular, we investigate the statistical properties of multi-mode twin-beam states in the mesoscopic regime [3] and assess the performance of the new generation of Silicon Photomultipliers, a class of photon-number-resolving detectors [4]. One of the drawbacks of these devices is the optical cross-talk, i.e. the occurrence of events from avalanches triggered by Bremsstrahlung radiation [5]. We show that an estimate of the cross-talk probability, as well as of the mean number of dark-count events, can be provided through a suitable formulation of the autocorrelation function.

Moreover, we demonstrate that the autocorrelation function for the photon-number difference can be used as a nonclassicality criterion for correlations [2].

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A new version of quantum mechanics with definite macroscopic states

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In accordance with the Bohr's standard interpretation [1, 2], which assumes the full symmetry of the entanglement relationship between quantum entities and the "agencies of observation", the conventional quantum-mechanical formalism does not contain prescriptions that differentiate the use of the concept of probability amplitude when applied to atomic entities or to macroscopic bodies. Paradoxes much discussed in literature, such as that of Schrödinger's cat [3], originate in this context.

The symmetry indicated by Bohr can be broken in ways that preserve unitarity, as in the usual decoherence program. We consider a different approach [4], based on three principles: (1) the interpretation of the amplitude collapse as a real, non-unitary physical phenomenon that converts quantum information into classical information; (2) the identification of this phenomenon with the "quantum jump" already introduced by Bohr and well demonstrated experimentally in quantum optics [5]; (3) an ontology of events *à la* Russell-Whitehead [6] applied to quantum jumps. This last point allows to redefine, in an appropriate reformulation of quantum mechanics, the macroscopic bodies as "galaxies of quantum jumps" (to use a metaphor of J.S. Bell). Thus a distinction is made between the probability amplitudes associated with individual events not yet actualized and the projectors associated with the relatively stable properties of "galaxies" of actualizations. The amplitudes introduced to express these projectors may not be subject to the superposition principle.

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Optimal measurements for quantum fidelity and quantum Fisher information of Gaussian states

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Quantification of similarity between two quantum states is important to assess various applications of quantum information processing such as quantum communications and quantum error correction. Among diverse measures for similarity, quantum fidelity is the most widely used. It is defined as the minimal overlap of two probability distributions obtained by measurements on two given states. Thus, finding optimal measurement that minimizes the overlap is crucial to estimate quantum fidelity.

In this work, we find a closed form of optimal measurements for quantum fidelity between two arbitrary Gaussian states, known as a practical resource for various quantum information processing applications. The general results are more specified for single-mode Gaussian states, and we show that there are three distinct types of optimal measurements: an excitation-number-resolving detection, a projection on the eigenbasis of the operator $xp+px$, and a quadrature variable detection, each of which corresponds to different types of single-mode Gaussian states.

Moreover, we show the equivalence between optimal measurements for quantum fidelity and those for quantum Fisher information. The equivalence significantly simplifies the derivations of quantum Fisher information and associated optimal measurements. Finally, we exploit the equivalence to find the optimal measurements for displacement, squeezing, phase, and loss parameter estimation using Gaussian states.

We finally propose implementable measurement setups for phase estimation using Gaussian states. Since an experimental construction of the projectors on the eigenbasis of $xp+px$ is not yet feasible, we alternatively employ a projection synthesis technique and a variant of general-dyne detection, known to be implementable within current technology. We find the optimized set of projectors outperforms any Gaussian measurements for phase estimation.

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Fluctuating Quantum Mechanics

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The interest for a deeper understanding of the conceptual and physical foundations of quantum mechanics is closely related to the achievement of an unifying picture of the physical phenomenology, from the subatomic to the classical levels. This issue implies an a priori metaphysical ansatz on the existence of a physical reality, independent of any observer and any process of measurement [1], which is by no mean neither trivial nor generally accepted.

The physical issues raised by the complementarity principle, by the wavefunction collapse, by quantum nonlocality and its relation with the Hermitian structure of quantum operators associated with physical observables [2], albeit distinct in nature, and requiring specific mathematical physical tools for their analysis, push towards one and the same physical question, namely the achievement of a unifying picture of the physical world, encompassing both quantum and classical systems, particles and fields, beyond the mere technical way of making quantitative predictions of the outcome of experiments from the quantum machinery.

In this presentation we explore the possibility of describing quantum mechanics in terms of classical field theory, or more precisely as a thermodynamic “equilibrium” problem involving two field phases. This attempt is in line with the analysis of Laughlin and Pines on the emergent characters of physical laws, including quantum physics [3].

The above mentioned model provides a radically different interpretation of quantum equations of motion, namely a classical field-theoretical interpretation of the Schr¨odinger equation, in which quantum (field) fluctuations still play a leading role, but a quantum system is viewed through the cohexistence of two field-phases.

This ansatz originates from the approach developed by Born and Infeld [4] on a field-theoretical unification of physical reality, albeit it is radically different from the Born-Infeld theory.

In the present thermodynamic model we assume that a quantum system corresponds to a twophase thermodynamic system in which a distributed (radiating) field coexists with a condensed field phase. Quantum equation of motion emerges from the interaction between the two phases by assuming a quasi steady-state approximation. As regards the condensed phase, it is at present described in a particle-like way via position and momentum. This aspects of the formalism will be hopefully generalized in forthcoming works.

As mentioned above, from a quasi-state approximation on the statistical description of the condensed field phase, Schrodinger equation is recovered. More precisely, a system of hyperbolic first-order equations analogous to the statistical description of generalized Poisson-Kac processes [5] is derived. The Kac limit of these equations provides the classical Schrodinger model containing the Laplacian operator accounting for the kinetic energy.

Several interesting properties follows from this approach:

• A fully classical derivation of the Schr¨odinger equation is proposed.

• The model deriving for this thermodynamic approach is indeed relativistically consistent and possesses finite propagation velocity.

• The extension of the theory beyond the quasi steady-state approximation could provide new insight on the wavefunction collapse and the semiclassical limit.

Relativistic Independence – A new framework for analyzing nonlocality

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If Nature allowed nonlocal correlations other than those predicted by quantum mechanics, would that contradict some physical principle? Various approaches have been put forward in the past two decades in an attempt to single out quantum nonlocality. However, none of them can explain the set of quantum correlations arising in the simple scenarios. Here it is shown that generalized uncertainty relations, as well as a specific notion of locality give rise to both familiar and new characterizations of quantum correlations. In particular, we identify a condition, relativistic independence [1], which states that uncertainty relations are local in the sense that they cannot be influenced by other experimenters' choices of measuring instruments. We prove that theories with nonlocal correlations stronger than the quantum ones do not satisfy this notion of locality and therefore they either violate the underlying generalized uncertainty relations or allow experimenters to nonlocally tamper with the uncertainty relations of their peers.

We employ this framework for deriving new bounds on quantum and post-quantum correlations [2,3], for proposing a novel family of multiplicative Bell inequalities [4], and for analyzing entangled networks and other complex systems.

An experimental scheme for testing some of the above theoretical predictions is presented. It employs a quantum optics experiment for realizing sequential weak measurements [5] on entangled photons.

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Completely top–down hierarchical structure in quantum mechanics

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Can a large system be fully characterized using its subsystems via inductive reasoning? Is it possible to completely reduce the behavior of a complex system to the behavior of its simplest "atoms"? In this talk I'll answer these questions in the negative for a specific class of systems and measurements. After a general introduction of the topic, I'll present the main idea with a simple two-particle example, where strong correlations arise between two apparently empty boxes. This leads to surprising effects within atomic and electromagnetic systems. A general construction based on pre- and postselected ensembles is then suggested, wherein the *N*-body correlation can be genuinely perceived as a global property, as long as one is limited to performing measurements which we term "strictly local." I'll conclude that under certain boundary conditions, higher-order correlations within quantum mechanical systems can determine lower-order ones, but not vice versa. Surprisingly, the lower-order correlations provide no information whatsoever regarding the higher-order correlations. This supports a top–down structure in many-body quantum mechanics.

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Hybrid Superconducting Microwave Resonator – Nanowire Quantum Dot Systems

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Single electron transistors made of semiconducting quantum dots (QDs) are ultimate components for which the extensive electrical control of charge, orbital and spin degrees of freedom is obtained. Bottom-up grown InAs/InP nanowires (NWs) have emerged as a reliable way to produce heterostructured single and double quantum dots, typically characterized by a large single particle energy spacing with Coulomb and Pauli blockade detectable up to 50 and 10 K, respectively.[1] The intrinsic quantum features of these systems and the possibility to integrate these nanodevices into multifunctional architectures are very appealing for quantum technologies. In particular, the large spin-orbit coupling in InAs NW QDs potentially allow the direct coupling between single electron spins and microwave photons. Single-atom MASERS and single-photon detectors have also been proposed by exploiting the electron transitions between discrete QD levels upon emission or absorption of microwave photons.

These experiments typically require the coupling between QD and a well-defined microwave mode. Here we present design and realization of a hybrid device in which InAs/InP NW QDs are fabricated in correspondence to the electric antinode of a superconducting coplanar resonator. In particular, we have used YBCO films that are suitable for the fabrication of magnetic field resilient coplanar resonators and that have already been tested for circuit quantum electrodynamics experiments with spin systems.[2] The resonator provides an alternate voltage fluctuation to the dot's leads at the frequency of the fundamental mode (9.815 GHz). We have investigated the transport features of single NW QDs in the presence of the microwave drive. By focusing on charge states with either radial or axial orbitals, we have observed a different response to the cavity field and the splitting of the Coulomb diamonds. We interpret these results as an effect of the different longitudinal momentum of the QD states involved.[3]

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A complex nonlinear approach for understanding quantum physics

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To understand quantum phenomena namely the particle-wave duality, in a causal elational way, a nonlinear complex process was proposed by de Broglie. This process rejects the ontic status of the Cartesian linear method in which the whole is assumed to be the simple linear combination of the parts and the action is equal and opposite to the reaction. The parts presumed naturally to maintain always its own identity no matter the interaction process.

This complex nonlinear inter-relational process was, in a certain way, proposed by many thinkers of the past. Namely, Heron of Alexandria with his principle of shortest path, Pierre de Fermat with his principle of least time and the extreme or optimal principles from which classical mechanics may be derived. The Broglie advanced the guiding, or pilot wave principle as the very basis for explaining the quantum duality. This general way to help us to better understanding Nature at diverse scales of bservation and levels of description may now be generalized under the name of principle of eurhythmy.

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Challenging Quantum Mechanics underground by hunting X Rays whispers in the cosmic silence

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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 the most 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.

I shall present our method of searching for possible small violations of the Pauli Exclusion Principle (PEP) for electrons, through the search for "prohibitted" 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 experimental test with Germanium detectors measuring lead target.

I shall then present and discuss new 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 I'll discuss the experimental limits we found by considering the Penrose-Diosi related model.

System Parameter Optimization for Minimization of Sign Error Probability in Free Space Optical CV-QKD

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Quantum Key Distribution (QKD) is a communication method that exchanges secret keys using cryptographic protocols involving elements from quantum information science. Continuous Variable (CV) QKD is a method to implement key exchange using sampling of Gaussian signals. Information Reconciliation (IR) is necessary to ensure Alice and Bob (legitimate parties in information exchange) have nearly identical copies of secret keys. In Free Space Optics (FSO) setting, IR aims to overcome channel problems such as pointing jitter or atmospheric turbulence, and it could be done by one-way or two-way channel coding over a public authenticated channel by exchanging some bits between Alice and Bob. The stream of bits after IR is denoted as *reconciled key*. Previously, we analyzed the problem of information reconciliation for CV-QKD over a FSO channel, studying the performance in terms of the sign error probabilities of the Gaussian samples shared between Alice and Bob. We found that the performance was strictly related to some system level parameters. In this work, we want to reinforce the relation between performance and these parameters and perform optimization to try to find the best ranges for these parameters.

Facets of bipartite nonlocality sharing by multiple observers via sequential measurements

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An intriguing property of quantum correlations is that they are monogamous in nature. The restriction on sharing Bell-nonlocal correlations between spatially separated observers is quantitatively expressed through the monogamy relations for Bell-nonlocality [1]. In case of the multipartite scenario considered in the monogamy context, n observers share n number of particles, one particle per each observer, and all the observers are spatially separated. Hence, the no-signalling condition (the probability of obtaining one party's outcome does not depend on spatially separated other party's setting) is satisfied between any pair of observers.

Recently, it has been shown [2, 3] that the monogamy relations no longer hold for the correlations obtained from measurements performed by different parties if a different scenario is considered where the no-signalling condition is relaxed between a subset of observers. Here, relaxing the no-signalling condition does not imply violating relativistic causality, rather it implies a scenario where sequential measurements are performed by different observers on the same particle. Specifically, the scenario is that one observer (say, Alice) has access to one half of an entangled system of two spin-1/2 particles, whereas, multiple observers (say, multiple Bobs) can access and measure on another half of that entangled system sequentially. Here Alice is spatially separated from multiple Bobs. In this scenario it has been shown [2, 3] that at most two Bobs can demonstrate Bell-nonlocality with single Alice when each Bob performs different measurements with equal probability and when the measurements of each Bob are independent of the choices of measurement settings and outcomes of the previous Bobs. This result has also been confirmed by experiment [4, 5]. Note that the above result is probed through the quantum violations of CHSH inequality [6], i. e., in the scenario where each observer performs two dichotomic measurements.

In the present study we investigate how many Bobs can sequentially demonstrate Bell-nonlocality with single Alice in the above scenario when the number of measurement settings performed by each observer is increased. The interesting result revealed by the present study is that the maximum number of Bobs, who can demonstrate Bell-nonlocality with single Alice, remains unchanged when the number of measurement settings performed by each observer is increased. In other words, no advantage over CHSH inequality is gained in the context of sharing of Bell-nonlocality when different Bell-type local realist inequalities with different number of dichotomic measurements per observer are used.

One important point to be stressed here is that sharing of Bell-nonlocality [2, 3] has been probed assuming that Alice and multiple Bobs initially share pure maximally entangled state. However, in real practical scenario it is very difficult to prepare pure maximally entangled state. Hence, in order to incorporate inaccuracies that appear in real scenario, we also investigate sharing of Bell-nonlocality by multiple Bobs with single Alice in the above scenario, when Alice and multiple Bobs initially share nonmaximally entangled pure state or mixed state. The robustness of different Bell-type local realist inequalities in the context of sharing of Bell-nonlocality against entanglement and mixedness of the initial shared state is explored in the present study. Interestingly, we have shown that CHSH inequality is the most robust against entanglement and mixedness of the initial shared state in the context of sharing of Bell-nonlocality

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Fault-tolerant quantum metrology

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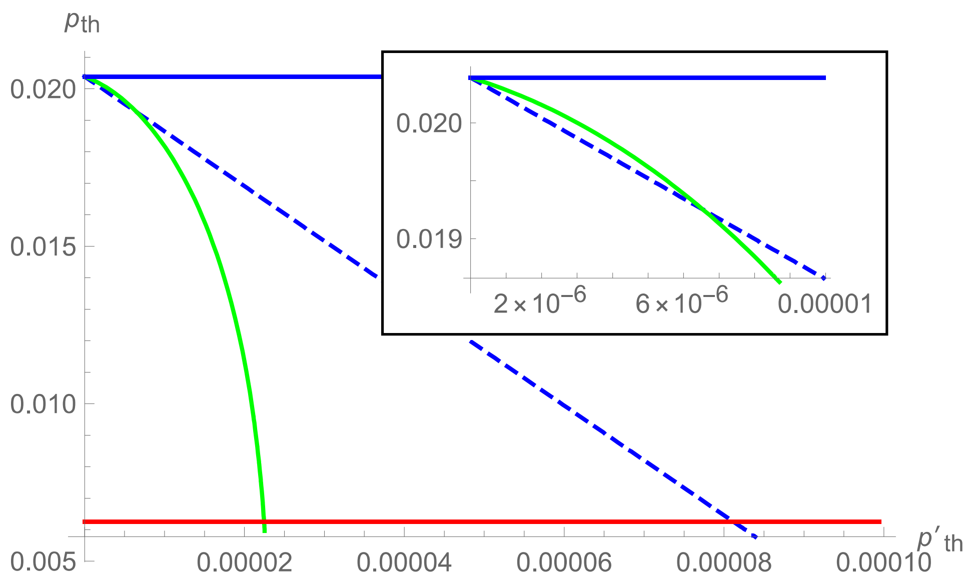
We show how fault-tolerant quantum metrology can overcome noise beyond our control – associated with sensing the parameter, as well as under our control – in preparing and measuring probes and ancillae. To that end, we introduce for the first time noise thresholds to quantify the noise resilience of parameter estimation schemes. We demonstrate improved noise thresholds over the non-fault tolerant schemes. We use quantum Reed-Muller codes to retrieve more information about a single-phase parameter being estimated in the presence of full-rank Pauli noise and show that better devices, which can be engineered, can enable us to counter more noise in the field beyond our control.

Our main result in presented in the following graph. Let p_{th} and p'_{th} denote the noise thresholds for the field we sense and the devices used for the sensing respectively. The red line denotes the threshold for phase estimation in the absence of any external noise. The solid blue line denotes the same for fault-tolerant phase estimation in the presence of field noise only, with the devices being perfect. The dashed blue line denotes the threshold for phase estimation in the presence of noisy devices, with fault-tolerance applied only to the field. As expected, the thresholds drop with increasing device noise. Finally, the green line shows the thresholds for noise everywhere being combated by fault tolerance everywhere.



The region and magnitude of the improvements of fault-tolerant quantum metrology is rather small. Further improvements in fault-tolerant quantum metrology could be achieved by optimising in tandem parameter-specific estimation schemes and transversal quantum error correcting codes. Our work however illustrates, for the first time that this is indeed possible.

For details, see https://arxiv.org/abs/1807.04267

Facets of bipartite nonlocality sharing by multiple observers via sequential measurements

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Recently, it has been shown [2, 3] that the monogamy relations no longer hold for the correlations obtained from measurements performed by different parties if a different scenario is considered where the no-signalling condition is relaxed between a subset of observers. Here, relaxing the no-signalling condition does not imply violating relativistic causality, rather it implies a scenario where sequential measurements are performed by different observers on the same particle. Specifically, the scenario is that one observer (say, Alice) has access to one half of an entangled system of two spin-1/2 particles, whereas, multiple observers (say, multiple Bobs) can access and measure on another half of that entangled system sequentially. Here Alice is spatially separated from multiple Bobs. In this scenario it has been shown [2, 3] that at most two Bobs can demonstrate Bell-nonlocality with single Alice when each Bob performs different measurements with equal probability and when the measurements of each Bob are independent of the choices of measurement settings and outcomes of the previous Bobs. This result has also been confirmed by experiment [4, 5]. Note that the above result is probed through the quantum violations of CHSH inequality [6], i. e., in the scenario where each observer performs two dichotomic measurements.

In the present study we investigate how many Bobs can sequentially demonstrate Bell-nonlocality with single Alice in the above scenario when the number of measurement settings performed by each observer is increased. The interesting result revealed by the present study is that the maximum number of Bobs, who can demonstrate Bell-nonlocality with single Alice, remains unchanged when the number of measurement settings performed by each observer is increased. In other words, no advantage over CHSH inequality is gained in the context of sharing of Bell-nonlocality when different Bell-type local realist inequalities with different number of dichotomic measurements per observer are used.

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NV, SiV and GeV centers incorporated into CVD nanodiamonds : study of the growth process and the optical properties.

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In the last years, diamond has been considered very attractive for a variety of applications in the field of quantum technologies thanks to its ability to incorporate luminescent color centers with outstanding physical and optical properties. For example, Nitrogen-Vacancy (NV) centers in diamond are promising luminescent defects allowing potential breakthrough applications in magnetic sensing, information processing and quantum cryptography. Indeed, these single photon emitters (637 nm) have electronic spin states that can be optically manipulated at room temperature. Incorporating color centers into nanodiamonds can open the way to the development of special devices, such as magnetic probes with nanoscale resolution [1], biomarkers providing wide field magnetic imaging [2] or hybrid quantum devices for quantum information processing and quantum cryptography [3]. Currently two techniques have been successfully developed for diamond nanoparticles production: detonation and milling of bulk particles which ensures small size and relatively useful optical properties, but which present also some limits in terms of composition control and luminescent center incorporation [4].

In this work a different way to produce diamond nanoparticles containing several kinds of luminescent defects (NV, SiV and GeV) is proposed by the direct plasma assisted CVD growth. By this technique we can get a good control of both nanoparticle growth processes and color centers formation. The CVD nanodiamond growth process optimization is presented showing the impact of different plasma parameters and gas phase composition on the nanoparticle crystallinity, size and shape. Morphological characterizations evidence the production of small (around 100 nm) and well faceted nanodiamond particles. In addition we show for the first time that NV, SiV and GeV color centers can be incorporated and their density tuned within this material by varying the gas phase composition. These results emphasize the high flexibility of the CVD growth technique. Eventually, the optical properties of the incorporated color centers have been assessed both at room and cryogenic temperatures in order to evaluate their suitability for quantum technology applications.

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Sum rules and coset functions in multiphoton interferometry

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I will discuss sum rules in photon coincidence rates in the context of interferometry. These can be evaluated using group coset functions and sums of immanants of the scattering matrix describing the optical network. In particular, we will show how the scattering matrix can be replaced with a coset matrix containing 0s, a feature that simplifies the evaluation of immanants. We will also discuss how the sum rule can be expressed in terms of sums of moduli squared of immanants

Approaching the Quantum Precision Limit in the Estimation of Quantum States

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The Gill-Massar inequality allows us to obtain a lower bound for the accuracy in the estimation of quantum states by means of separable measurements. A central problem is the development of estimation strategies that saturate, or closely approach, this fundamental bound.

Here, we propose two methods for the estimation quantum states of high dimensional quantum systems that reach an accuracy comparable to the Gill-Massar lower bound.

The first method allows us to estimate unknown pure quantum states of a d-dimensional quantum system with an accuracy, quantified via the infidelity, that asymptotically approaches the Gill-Massar lower bound $I=(d-1)/N$ for pure states, with N the size of the ensemble of identically, independently prepared copies of the unknown state [1,2]. The method is iterative and adaptive in nature and based on a combination of optimization on the field of complex numbers and statistical inference via maximum likelihood. Convergence toward I_{GM} arises after 8 iterations for moderate dimensions.

The second method is designed to estimate unknown mixed quantum states of high dimensional quantum systems. This method is based on the adaptive application of standard quantum tomography. In a first stage, an ensamble of size N_0 is employed to obtain a first estimate of the unknown state. The eigenstates of this estimate are then employed to represent the relevant operators in a second stage of standard quantum tomography, which is carried out on an ensemble of size $N-N_0$. The new estimate is characterized by an infidelity that behaves as O(1/N) for all quantum states [3]. Thereafter, we show that a suitable choice for the bases employed in standard quantum tomography leads to an infidelity that is twice the Gill-Massar lower bound $I=(d^2-1)(d+1)/4N$ for mixed states, for all dimension d [4,5].

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

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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 leptons based on the SU(2)*U(1) as well as on the conformal groups of Weyl’s transformation leads to an intriguing 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 proportional 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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The Cosmological Constant: Temperature effects on the Higgs field

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The dynamical properties of the Universe are described in fully geometrical terms of a Lagrangian function accounting for the Yang-Mills field of the electro-weak theory of the elementary particles. A Higgs mechanism within a symmetry-breaking process offers formal connections between some relevant properties of the elementary particles and the Cosmological Constant. By our model the celebrated " Λ-*paradox*" is solved by consideration of the Universe cooling during the expansion following the onset of the electro-weak phase transition.

Topological quantum walks in the two-dimensional transverse momentum space of photons

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Quantum Walk processes are promising platforms for simulating condensed matter physics phenomena, like topological phases of matter [1]. A Quantum Walk consists in the evolution of a quantum state defined on a lattice ("walker space") whose dynamics is conditioned by an internal degree of freedom. Different solutions have been introduced for the realization of Quantum Walks in photonic platforms [2]. Among these, only a few allowed to extend the walker space to a two dimensional lattice. Here we present a new platform that achieves this task by employing an intrinsically two-dimensional degree of freedom: the transverse momentum of light, associated to the projection of the wavevector on the transverse plane. To realize the quantum walk we implement shift operators that change the transverse wavevector in a way conditioned by the input polarization state. This is achieved by liquid crystal based polarization gratings, called "g"-plates, which increase or decrease the amount of transverse linear momentum if the input polarization is left circular or right circular, respectively. Our platform presents different adjustable parameters and can be used to explore different Quantum Walk processes, exploitable for quantum simulation and information. In particular we devise a protocol that, for some values of the system parameters, exhibits non-trivial topological phases, associated with a non-zero Chern number. Hence, we can investigate the physics of periodically driven Anomalous Quantum Hall Insulators. In particular, by simulating the effect of an external force, we observed an anomalous displacement of the ground state mean position, that it is known to be proportional to the Chern number. Our results pave the way to exploit quantum walks for the investigation of topological physics of static and Floquet systems in two spatial dimensions.

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Novel single-photon-emitting defects in diamond

S. Ditalia Tchernij et al. [1]*, J. Forneris et al. [2], J. Meijer et al. [3], M. Jakšić et al. [4], M. Genovese et al. [5], G. Verona Rinati et al. [6]

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Diamond is a promising platform for the development of technological applications in quantum optics and photonics. The quest for new color centers with optimal photo-physical properties has led in recent years to the search for novel impurity-related defects in this material, with the purpose of enabling the fabrication of specific luminescent defects upon a controlled ion implantation process. Particularly group–IV-impurity-related color centers like Si-V and the recently discovered Ge-V have attracted a broad interest in the last years thanks to their short lifetimes and narrow spectral emission lines. In this contribution, we report on our recent progresses at the fabrication and characterization of novel classes of quantum emitters in single-crystalline diamond based on Sn [1] and Pb [2] color centers. These color centers share many of their opto-physical properties with the other group IV impurities, such as a short lifetime and a narrow spectral emission, while being characterized by a higher brightness. The attribution of the newly discovered optical centers to Sn- and Pb-based defects was performed through the correlation of their photoluminescence (PL) intensity with the implantation fluence. Hanbury-Brown&Twiss interferometry measurements confirmed the single photon emission from isolated defects located in ion implanted areas. Moreover a study of non-classical emission as a function of excitation laser power revealed that both Sn- and Pb-related defects consist of three-level systems with 5 ns radiative decay lifetimes. These results represent a significant step towards completing the interpretational frame work on the optical activity of diamond defects related to group IV impurities.
Moreover we report the fabrication by means of ion beam implantation and optical characterization of new optically active defects based on He impurities [3][4]. These defects have desirable spectral features for single photon sources but this defect behavior and structure is still to be fully understood. For this reason low temperatures optical measurements have been performed as well as the study of the Stark shift effect on the spectral lines. Future studies on these defects properties at the single-photon emitter level could lead to appealing perspectives in the fields of quantum information processing and quantum sensing.

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Verifying boson samplers and other near-term quantum devices

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Recent years have seen an enormous interest in near-term quantum devices that could show a quantum speedup over classical computers with realistic means. This constitutes an important milestone in endeavors to achieve quantum devices that are superior to supercomputers and practically useful. Boson samplers in which photons are sent through linear optical multiports is an important example of such a device, and so are instances of quantum simulators, some also realized with quantum optical means. In this talk, we will address the key aspect of how to verify the correct functioning of such near-term devices (being faithful to the quantum information and sensing theme of the conference). We will see that boson sampling cannot be black-box verified at all, by looking at outcomes of measurements alone, giving rise to a highly ironic situation [1]. We briefly look at how near-term devices could possibly be verified, and hint at a new proposal deriving from frequency combs [2,3]. In an outlook, we hint at the problem of rigorous and stable Hamiltonian learning in quantum simulators, as we are pursuing together with experimentalists [4].

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Hybrid entanglement with time-bin coding

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Light is an extremely convenient support to carry as well as manipulate Quantum Information. Traditionally, information can be coded in two ways. With the "discrete variable" (DV) approach, "qubits" are coded in discrete spectrum observables, while "continuous variables" (CV) rely on continuum spectrum observables, such as the electric field. In both cases, entanglement is a key resource for the perspective of practical quantum technologies. Hybrid DV-CV states are the result of the entanglement between discrete and continuous variable subsystems.

Discrete variables benefit from tolerance to losses but generation and detection are probabilistic. Continuous variables allow deterministic generation and measurement but largely suffer from losses. Hybrid states permit designing protocols that take the advantages of both coding strategies by limiting their individual drawbacks [1].

Experimental realizations of photonic hybrid states have already been accomplished, where the discrete part is either encoded using the presence or absence of a photon [2, 3] or on single photon polarization states [4, 5]. For practical applications in telecom fibers, none of those strategies is fully satisfactory; single-rail encoding suffer from losses and detector inefficiency while polarization is not maintained during propagation [6].

We present an experimental scheme to generate hybrid entanglement, with the discrete part coded in the time-bin observable. Our proposal is based on the interference between an optical Schrödinger cat and a time-bin entangled pair of photons, followed by single-photon measurement. Conveniently, we stress that the hybrid state is heralded and doesn't require any post-selection process. We also analyze the impact of experimental imperfections on the generation scheme and demonstrate that our scheme is robust against the presence of vacuum and multiple pair generation in the discrete part input, thus allowing to work with standard photon pair sources based on non-linear optical process.

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A More Fundamental Reality Beneath Quantum Phenomena? Theory and Experiment

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The fact that the Two-State-Vector Formalism (TSVF) yields greater information about a quantum evolution has been known for many years. Under pre- and post-selection, where information from both past and future measurements is used, even noncommuting variables can be determined for the same instant. And under special pairs of such selections, even more exotic quantum variables are shown to prevail. The problem, however, was with the validation of these derivations. Weak measurement was designed to reveal the delicate between-measurements value without causing the ordinary measurement's disturbance. Yet this method was not universally accepted on the grounds that the outcome is nevertheless weakly affected by the weak measurement. Recently, however, ordinary measurements were shown to be able, in some cases, to achieve this task as well. Their results are therefore immune to the above criticism. I present a case where TSVF makes a very extraordinary claim: A particle goes through a middle segment of a path without entering its beginning neither exiting from its end. A fairly simple measurement with the aid of a probe particle is indeed obliged to indicate the target particle's paradoxical sequence of absence, presence and again absence, along this path. Even more extraordinary is the mathematical formalism underlying this dynamics. The particle's superposition turns out to comprise a multiplicity of temporary "mirage particles," of which some have negative mass. Wavefunction "collapse" and Interaction-Free Measurement thus gain a fresh explanation as mutual cancellations and enhancements between these mirage particles. I describe a few experimental settings proposed to demonstrate this dynamics, as well as a few preliminary results.

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Interacting quantum models by approximation from multipartite cellular automata

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The Cellular Automaton Interpretation of Quantum Mechanics by G. 't Hooft assumes the existence of ontological states of a physical object. They are exemplified in a class of discrete deterministic Hamiltonian cellular automata, which have such features in common with continuum quantum mechanical models as linearity, superposition principle, symmetries, and the Born rule. Ontological states evolve by permutations among themselves without creating superposition states. The latter belong to the mathematical language commonly used, i.e. quantum theory. This seems to imply that only very primitive non-interacting multipartite models are conceivable, composed of discretized free harmonic oscillators, which would widely differ from interacting quantum field theories, for example. – However, we consider systems composed of multiple two-state Ising spins that evolve classically by permutations in a possibly large but fixed space of ontological states. We show that this dynamic becomes the one of an interacting quantum many-body system or field, when approximated by truncations of Baker-Campbell-Hausdorff formulae applied to extract a Hamilton operator from the unitary transfer matrix.

Keywords: cellular automaton; Ising model; Baker-Campbell-Hausdorff formula; ontological state; quantum mechanics

Evidence in quantum data

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The data acquired in quantum experiments are unavoidably affected by statistical fluctuations and, therefore, the interpretation of the data must rely on methods from statistics. While p-values and confidence intervals are routinely reported, this practice is questionable. Bayesian concepts, instead, fit quite naturally to quantum data. This talk deals with various aspects of Bayesian methodology, in particular with the Bayesian notion of what constitutes evidence in favor of, or against, a hypothesis.

Spatial entanglement patterns and Einstein-Podolsky-Rosen steering in a Bose-Einstein condensate

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Entanglement is an essential resource for quantum technologies such as quantum metrology with atomic clocks and interferometers [1]. At the same time, it is a fundamental concept of quantum physics that still presents conceptual challenges, in particular when applied to many-body systems of indistinguishable particles. For example, spin-squeezed and other non-classical states of atomic ensembles were used to enhance measurement precision in quantum metrology, but the notion of entanglement in these systems was debated because the correlations between the indistinguishable atoms were witnessed by collective measurements only [2].

In this work [6], we experimentally prepare two-component Rubidium-87 BECs, consisting of a few hundred atoms, on an atom-chip [3]. Using state-selective potentials to tune the collisional interactions (one-axis twisting dynamics), we prepare many-particle non-classical states [4]. After a time-of-flight expansion, high-resolution images allows us to access sub-regions of the atomic density distribution of various shapes and measure the spin correlations between them.

We observe that bi-partitions violate a separability criterion, showing the presence of entanglement between different spatial regions of our many-body system. In some of such partitions, entanglement is strong enough for Einstein- Podolsky-Rosen steering: measurement outcomes for non-commuting observables in one spatial region can be predicted based on a corresponding measurement in the other region with an inferred uncertainty product below the Heisenberg relation [5]. This feature could be exploited for imaging of electromagnetic and other field distributions with an uncertainty beyond the standard quantum limit.

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Interfering trajectories in experimental quantum-enhanced stochastic simulation

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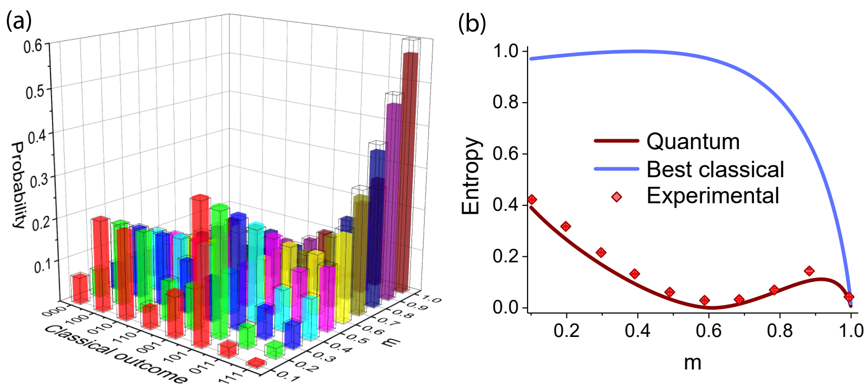
Stochastic processes, such as weather patterns and traffic congestion, describe numerous phenomena in science where the quantity of interest varies discretely or continuously through time in a probabilistic fashion. Therefore, predicting the future behaviour of stochastic processes has always been on demand. The general methodology for prediction is to observe the process and then use this information to predict the future. Classical simulators, in terms of the amount of data they need to store to predict, are very demanding and wasteful [1, 2]. Using quantum tools provides a reduction in the amount of memory required for these simulations [3]. We experimentally demonstrate this memory advantage via quantum simulation. In this work (which will appear in Nat. Commun.), we use a photonic quantum information processor to demonstrate the first quantum simulator capable of simulating a Markovian process for multiple discrete time steps. We show that this quantum simulator needs a memory storage less than the best classical simulator.

Here we simulate a simple Markovian stochastic process called the perturbed coin. This process consists of one binary variable (0 or 1) that represents the state of a coin. Crucially, our approach creates a coherent quantum superposition of the different possible futures trajectories over multiple time-steps. This conserves the entropy of the memory system throughout the simulation and allows a quantum memory advantage to be maintained. We highlight the advantage of the coherent superposition, by showing how it enables us to perform a second key task beyond statistical sampling. Given two (potentially different) stochastic processes, the output of our simulator lets us estimate the overlap of the statistical futures of two stochastic processes via quantum interference. To achieve this, we produced, controlled and interfered high dimensional quantum states with very high quality. Moreover, the capability of encoding a large amount of information on a multi-dimensional photonic state makes them important in the context of quantum information science [4]. We can use our processor for two tasks: 1) to simulate the future outputs over three time steps of the perturbed coin process, and 2) to estimate the overlap of the future output statistics. The experimental results are shown in the figure.



(a) Sampling the statistical future. The coloured bars show the experimental results of the sampled future after three steps, depending on the stochastic process parameter m . The transparent bars show the theoretical probabilities. (b) Entropy of the memory system, as the measure of the memory storage, for the quantum simulator, versus m values.

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Entanglement of multiphoton polarization Fock states and their superpositions.

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There is a growing interest in the science of quantum information to entangled quantum states with high numbers of photons. In this work we consider pure multiphoton polarization Fock states and their superpositions. We give a general definition of density matrices of such states as well as density matrices of mixed states arising from pure Fock states after their partial reduction over a series of photon variables. Elements of such density matrices are expressed in terms of correlators defined as averaged products of equal numbers of creation and annihilation operators. Parameters characterizing the degree of entanglement in such states are calculated, and their dependence is investigated on features of the original pure states and on the ways of their reduction.

Color Centers in Silicon Carbide: Pushing the Limits of Electrically Driven Single-Photon Sources

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A true single-photon source is an essential element of many quantum information devices. However, it is still a challenge to obtain bright, stable, and efficient single-photon emission under ambient conditions, which is required for practical applications. Currently, point defects in the crystal lattice of diamond known as color centers have taken the lead in the race for the most promising quantum optoelectronic system [1]. However, their electrical control and excitation are complicated [2], since diamond is a material at the interface between insulators and semiconductors. The demonstrated electroluminescence rates are lower than 50 kcps [3–5], and the recent theoretical studies show that such numbers can hardly exceed 2 Mcps at room temperature [2,6], which is not sufficient for high-performance quantum information devices.

In this work, we focus on a different material, namely silicon carbide, which has recently emerged as a novel platform for quantum photonics [7]. We perform a rigorous theoretical and numerical study of color centers in the crystal lattice of SiC diodes and reveal the physics behind the process of single-photon emission under electrical pumping [8]. We establish a theoretical framework and present it in a ready-to-use form, which can be easily adapted to any color center. The results of our numerical simulations accurately reproduce and interpret experimental observations on an existing single-photon emitting diode. Moreover, we show that color centers in silicon carbide can be far superior to any other quantum light emitter under electrical control at room temperature. We show that by introducing a p-i-n single-photon emitting diode with a graded doping profile, it is possible to increase the brightness of single-photon electroluminescence by four orders of magnitude and achieve a photon emission rate of up to 5 gigacounts per second at room temperature [8], which is significantly higher than what can be achieved with electrically driven color centers in diamond or epitaxial quantum dots. These results lay the foundation for the design and developments of practical quantum information devices which do not require cooling and operate under ambient conditions.

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Resource theory of Wigner negativity and applications in optomechanical systems

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The development of quantum information science aims at exploiting quantum features as technological resources suitable to process information. This endevour has led to the introduction of precise mathematical definitions for various notions of quantum resources, and manipulations thereof. In this talk, I will introduce a resource theory for infinite-dimensional (continuous-variable) quantum systems, grounded on operations routinely available within current technologies [1]. The present theory lends itself to quantify both quantum non-Gaussianity and Wigner negativity as resources. This framework finds immediate application in continuous-variable quantum computation, where the ability to implement non-Gaussian operations is crucial to obtain universal control. In this context, I will illustrate a scheme to arbitrarily process quantum information over mechanical oscillators (e.g., opto- and electro-mechanical systems, photonic crystals, trapped ions, ...) [2,3]. In particular, I will show how universal non-Gaussian gates can be unconditionally attained by making use of cubic non-linearities.

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Probabilistic Fault-Tolerant Universal Quantum Computation and Sampling Problems in Continuous Variables

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Continuous Variable (CV) systems are emerging as promising candidates for the implementation of quantum computation (QC) models. One of the main reasons for this interest relies in the possibility of generating deterministically large resource states such as cluster states, composed of up to one million modes [1].

Since the seminal paper by Lloyd and Braunstein [2], progress has been made to put CV QC on the same footing as qubit-based QC. One of the most important result in this direction is the paper by Gottesman, Kitaev and Preskill [3] who defined an encoding of qubits (GKP states) in a quantum harmonic oscillator. This encoding allows one to recover a *finite set of gates* sufficient for universal QC, although acting on an infinite dimensional space. Furthermore, *fault tolerance* can be reached using such encoded qubit states. However defining CV QC using the GKP states doesn't take advantage of the physics specific to infinite dimensional Hilbert spaces.

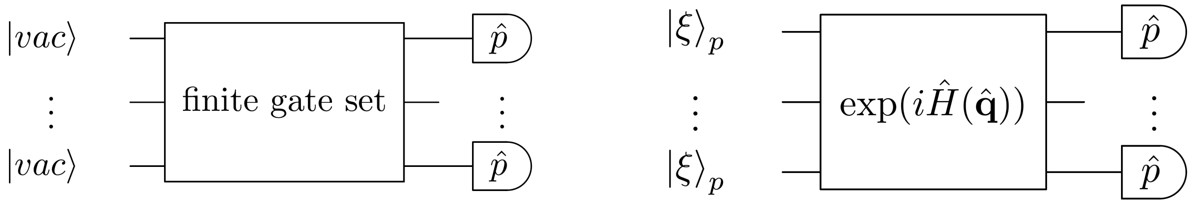

FIG. 1: Left: Schematic representation of a quantum computation in continuous variables. $|vac\rangle$ denotes the vacuum state of the associated quantum mode. We show that any quantum circuit with qubits can be reduced to a circuit composed of the aforementioned elements. Right: Instantaneous quantum computing in continuous variables. $|\xi\rangle_p$ denotes momentum squeezed vacuum states with squeezing parameter ξ. We show that sampling from the output distribution of such circuits is a hard problem for classical computers (unless the polynomial hierarchy collapses)

In this work, we first define a model of probabilistic universal fault-tolerant quantum computation in CV that does not explicitly require GKP states at the input [5]. More specifically, we show that a model composed of the following ingredients is sufficient for probabilistic universal QC: a set of modes initialized in the vacuum state, a polynomial number of gates drawn from a finite elementary gate set and homodyne detection. To ensure universality we show that any quantum circuit defined with qubits can be mapped onto a CV circuit made of those elements. We are also able to recover fault tolerance and to link the error threshold with the physical parameters of the model related to the definition of the set of gates.

Secondly, we use a similar construction to address quantum advantage in CV, and define two sub-universal models of quantum computation. The first one directly corresponds to the QC model addressed above but in the sampling scenario. The second computational model relies on momentum squeezed input states, an evolution described only by commuting gates diagonal in the position basis and homodyne detection of the momentum quadrature. The latter model corresponds to a CV analog of Instantaneous Quantum Polynomial time computations (IQP) [4, 6]. Crucially, the outcomes of the homodyne detection have to be discretized via binning to make sure that the sampling problem is well-defined. We prove that both sampling models are hard for classical devices, under the reasonable computer science assumption that the polynomial hierarchy does not collapse.

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Quantum non-Gaussian light and matter

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Quantum non-Gaussian light is an essential element for fundamental tests of light and matter and many applications in quantum technology. We propose its verification for multiphoton light and experimentally observe it from nine emitting processes. Further, we propose a faithful hierarchy of genuine n-photon quantum non-Gaussian light for connections between quantum devices and for diagnostic of multiphoton sources and processes in quantum technology. We faithfully experimentally witnessed genuine 3-photon quantum non-Gaussian light which cannot be obtained by any form of two photon emissions modified by Gaussian processes.

Fluctuation relations and detailed balance conditions for quantum thermalizing maps

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Consider finite-dimensional quantum systems in weak interaction with an external environment, subjected to an irreversible reduced dynamics described by one-parameter families of completely positive, trace-preserving maps possessing a unique, time-invariant asymptotic thermal state. For such general dynamics, quantum energy-fluctuation theorems can be obtained relating the probabilities of absorbing or releasing a certain amount of system energy in the environment; these novel fluctuation theorems are directly connected with the quantum version of the classical detailed balance condition.

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Spatially multimode SU(1,1) interferometer

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The standard precision in the measurement of a phase shift is offered by an interferometer with a coherent state of light used as a probe and can reach at best the so-called shot noise limit. It is possible to overcome this limit with the use of quantum resources, for instance employing a SU(1,1) interferometer, where optical parametric amplifiers are the active beam splitters and the squeezed light produced is the probe [1]. Yet the techniques developed by far in quantum metrology restrain the high sensitivity to a phase shift in one dimension [2], i.e. the linear displacement of an optical element.

We produce bright squeezed vacuum through the high-gain parametric down conversion (PDC) in a nonlinear crystal and, using a double-pass configuration, we build an SU(1,1) interferometer with a large angular bandwidth and a large number of spatial modes. The correction of the angular divergence of PDC in the first pass enables a two-dimensional phase-sensitive amplification/de-amplification of the spatially multimode radiation, while the mode content measured in the experiment remains stable as the phase changes. In comparison to previous arrangements [3], our construction features a richer spatial mode structure.

The potential applications of such a scheme range from imaging to remote sensing and quantum communication. In addition, the measurement of squeezing in different spatial modes is of great theoretical interest [4]. As a preliminary result, we demonstrate the quantum signature of this interferometer by measuring a quadrature squeezing of 3.9 dB through optical parametric amplification, which amplifies one quadrature while attenuating the other [5].

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Solvable model of a quantum particle in a detector

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The evolution of a quantum particle in a gaseous detector governed by the Schrödinger equation is studied by means of a simplified 3D model. The particle is assumed to interact with N excitable two-level point-like scatterers depicting the atoms [1]. In this model, the energy loss experienced by the particle after atomic excitations is accounted for. Using the Green function method, the full wave function is uniquely determined by $N \cdot 2^N$ complex numbers [1, 2, 3]. Remarkably, the Lippmann-Schwinger equation of this multi-scattering problem can be exactly solved in a non-perturbative way. The aim is to analyze the influence of the initial microstate of the detector on the observed outcome, and to understand the mechanism of track formation in gaseous detectors [4, 5].

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Engineering multimode entangled states in nonlinear photonic crystals

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Two-dimensional nonlinear photonic crystals enable a high flexibility for engineering classical and quantum properties of parametric processes. This work investigates the quantum state of twin photons generated by parametric down-conversion in a hexagonally poled nonlinear photonic crystal (HexNPC), pumped by two pump beams slightly tilted in the transverse direction (Fig.1). Due to the multiple quasi-phase matching (QPM) possibilities involving the two pump modes and the two fundamental vectors $\mathbf{G_1}$ and $\mathbf{G_2}$ of the hexagonal lattice, the spatio-temporal spectrum of the source shows a complexity by far exceeding conventional sources.

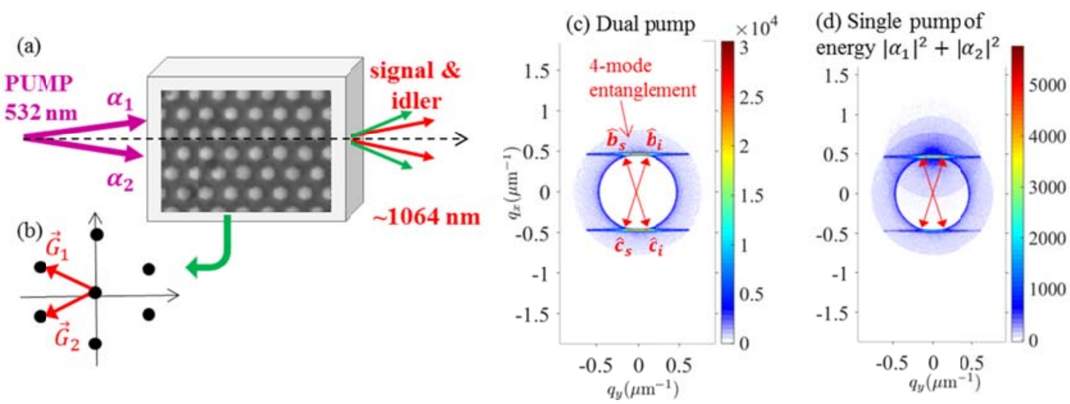

Fig. 1 a)Parametric generation in a hexagonally poled nonlinear crystal. b) Reciprocal lattice of the nonlinear pattern. Far-field distributions of the down-converted light from numerical simulations, for c) a dual pump, and d) a single pump with the same energy

We focus on a special *resonance* condition, where the transverse modulation of the pump matches that of the nonlinear pattern. Our analysis shows a significant enhancement of the down-conversion efficiency, in comparison to the use of a single pump with the same energy, over an entire branch of QPM modes (the ring in Fig.1c). This occurs because the resonant structure of the pump allows a maximal coherence between the two nonlinear processes coexisting in the HexNPC. In the same conditions, we demonstrate an unusual quadripartite entanglement among modes shared by different QPM branches (shared modes appear as line of hot-spots in Fig.1c,d). The action of the HexNPC is shown to be here equivalent to i) two independent parametric processes with different gains generating two pairs of entangled twin beams, followed by ii) an unbalanced beam splitter that mixes the outcomes. Both the parametric gains and the mixing coefficients can be controlled by varying the relative intensities and phases of the two pumps.

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Distributed Quantum Metrology with Squeezed States

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Exploiting the quantum features of light it is possible to boost the sensitivity of precision sensors beyond classical limitations [1,2,3]. The endeavor of developing quantum protocols capable of enhancing spatially separated measurements – a problem known as distributed quantum metrology – has recently sparked considerable interest. In practice, one is often interested in a linear combination of the results of several experiments held at different locations [4,5], e.g. in the inference of a field gradient or the spatial fluctuation of a field. We elaborate on the work in Ref. [6], proposing a quantum scheme for distributed quantum metrology with a linear optical network. Instead of photon-number sources as in Ref. [6], we make use of squeezed states, which are readily available in the laboratory and can be realized with a high mean photon number. Remarkably, our scheme is capable of estimating an arbitrary weighted sum of phases with non-negative weights and a precision scaling at the Heisenberg limit.

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Theoretical study of the optical-terahertz biphoton fields by means of the generalized Kirchhoff law.

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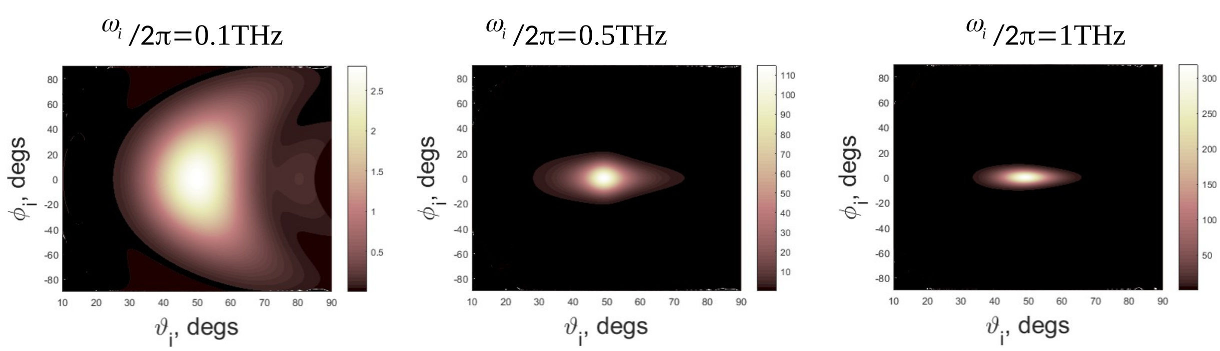
Correlated pairs of optical and terahertz-frequency photons can be generated via the spontaneous parametric down-conversion (SPDC) process in the strongly frequency non-degenerate regime[1,2]. We report results of theoretical study of the frequency-angular distributions of specifically terahertz-frequency idler photons and of the correlation characteristics of optical signal and terahertz idler fields emitted under non-collinear SPDC by a nonlinear crystal. Effects induced by classical thermal field fluctuations and the moderate level of inherent crystal absorption at idler frequencies are considered using the set of generalized Kirchhoff law (GKL) relations for parametric scattering by polaritons first obtained by D. N. Klyshko[3]. We have obtained the scattering matrix coefficients for SPDC in general case without paraxial approximation, accounting the transverse limited spatial profile of the Gaussian pump beam.

Caused by the spatial pump limitation, the multimode nature of parametric interaction between different signal and idler plane modes is shown to lead to a huge increase of angle divergence of the terahertz idler radiation. The counting rate measured at different polar (ϑ_i ¿ and azimuthal (φ_i¿angles is obtained as [4]

$$P_i^{Spon}(\vartheta_i,\varphi_i)=C_i\left(1+\langle N_T\rangle\right)\int S_\omega(\vartheta_i,\vartheta_s,\varphi_i,\varphi_s)\tan\vartheta_s\,d\vartheta_s\,d\varphi_s$$

by integration over the angular range of signal detection ϑ_s,φ_s of the sensitivity function $S_\omega(\vartheta_i,\vartheta_s,\varphi_i,\varphi_s)$, with account of the thermal field fluctuations by Plank's factor $\langle N_T\rangle = 1/\left[\exp(\hbar\omega_i/k_BT)-1\right]$. Examples of the sensitivity function distributions over idler angles, calculated at different frequencies and phase-matched signal angles for the case of SPDC in 1cm-long bulk Mg:LiNbO$_3$ crystal and the pump beam waist 1 cm, are presented in Figure. The angles are taken at the output of a special Si-prism coupler which has to be mounted at the lateral crystal surface for emission of idler radiation outside the crystal.



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All-Optical Implementation of Collision Based Evolutions of Open Quantum Systems

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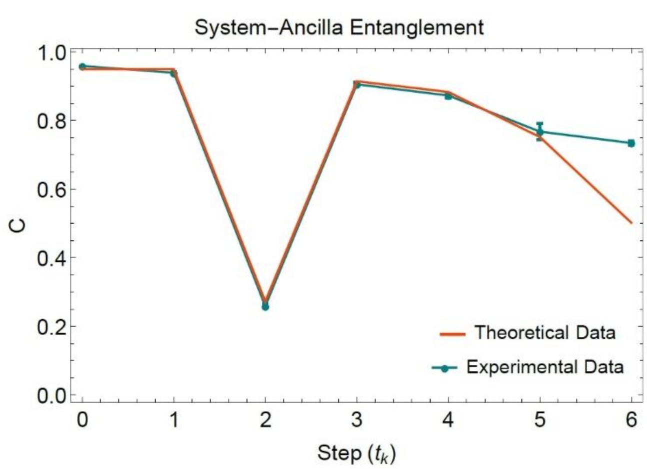
The control of the evolution of quantum systems is essential for future quantum information technologies. In general, the quantum dynamical process driving the evolution of a quantum system does not act only on the system itself, but also on the surrounding environment [1]. The system can interact with the environment and it is then called Open Quantum System (OQS). If the dynamic of an OQS is independent respect to previous continuous or discrete sections of the evolution it is called Markovian, otherwise it is called non-Markovian [2]. A powerful tool to simulate the interaction between system and environment is represented by the so-called collisional model (CM), in which the system-environment interactions happen only at discrete time [3].

We present an all-optical experimental implementation of the CM, based on two concatenated and displaced multipass Sagnac Interferometers (SIs), in which the interaction between system and environment is realized by mean of a bulk Beam Splitter (BS). The setup is stable in phase due to its Sagnac configuration, it is completely tunable in phase and different kinds of evolutions can be simulated adding optical elements to the setup, for example waveplates or attenuators.



In order to simulate the Markovian and non-Markovian dynamics we use pairs of entangled photons, one of which is injected in the setup while the other one behaves as the ancilla for an ancilla-assisted experiment. In the scheme, the system and the environment are encoded in different modes of the path degree of freedom of the photon circulating in the setup. We quantify the non-Markovian behavior of the evolution through the variation of the Concurrence (C) between system and ancilla [4]. The behavior of C for the realized non-Markovian dynamics is reported in Figure as a function of the steps of the evolution. Experimental data (blue line) agree with theoretical simulations (orange line), showing a clear revival of the entanglement level during the evolution. This confirms the possibility of using the setup to simulate OQS dynamics through a CM realized within an all-optical framework.

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Realization of Popper's EPR-like Experiment with Mesoscopic Pseudo-thermal Light

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We performed an experimental realization of Popper's thought experiment (PE) concerning the validity of Copenaghen interpretation of quantum mechanics. The profound analogy between Ghost Imaging (GI) with entangled beams and with thermal-like beams [1] allowed us to exploit the classical correlations between two beams generated from a pseudo-thermal source to perform both GI and Ghost Diffraction (GD) experiments only acting on the reference arm of the optical system [2, 3]. The experimental realization of PE can be achieved trough a GD scheme: to this aim, we employed a mesoscopic pseudo-thermal light divided at a beam splitter and an optical system where the diffraction pattern is produced by a double slit through a conventional diffraction scheme or a GD scheme. The adopted detection system consisted of optical fibers with different core diameters connected to hybrid photodetectors. In the reference arm we translated the fiber in order to achieve spatial resolution, while in the test one we kept the fiber fixed.

The diffraction patterns obtained either with conventional or ghost schemes are similar. We further compare our results with the literature[4-6].

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First observation of antimatter wave-interference

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In 1924 Louis de Broglie introduced the concept of wave-particle duality[1]: the Planck constant h relates the momentum p of a massive particle to its de Broglie wavelength $\lambda_{dB}=h/p$. The superposition principle is one of the main postulates of quantum mechanics; diffraction and interference phenomena are therefore predicted and have been observed on objects of increasing complexity, from electrons[2,3] to neutrons[4] and molecules[5]. Beyond the early electron diffraction experiments[2,3], the demonstration of single-electron double-slit-like interference was a highly sought-after result. Initially proposed by Richard Feynman as a thought experiment it was finally carried out in 1976[6]. A few years later, positron diffractionwas first observed[7]. However, an analog of the double-slit experiment has not been performed to date on any system containing antimatter. Here we present the first observation of matter wave interference of single positrons, by using a period-magnifying Talbot-Lau interferometer[8] based on material diffraction gratings. Individual positrons in the 8-14 keV energy range from a monochromatic beam were detected by high-resolution nuclear emulsions[9]. The observed energy dependence of fringe constrast proves the quantum-mechanical origin of the detected periodic pattern and excludes classical projective effects[10]. Talbot-Lau interferometers are well-suited to the experimental challenges posed by low intensity antimatter beams and represent a promising option for measuring the gravitational acceleration of neutral antimatter.

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Nanoscale BioPhotonics: using nanodiamond and fibre optics to understand the inner workings of the body

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Light-based imaging and sensing tools can assist with our understanding of the complex chemical and molecular processes taking place in and around cells in the living body [1]. Fluorescent nanodiamonds (NDs) are an attractive nanoscale-tool that have a range of unique properties which make them highly desirable for bioimaging and biosensing applications [2]. Their fluorescence is produced via optical excitation of atomic defects, such as the negatively charged nitrogen vacancy centre, within the diamond crystal lattice. Possessing long-wavelength emission, high brightness, no photobleaching, no photoblinking, nanometer size, a room temperature sensitivity to magnetic and microwave fields, and an exceptional resistance to chemical degradation make NDs almost the ideal fluorescent bioimaging nanoprobe [3]. I will discuss these exciting properties in detail and also give some recent examples of the effect of surface functionality on their fluorescent properties [4] along with their use as fluorescent probes for pH [5] and hydrogen peroxide sensing in biological systems [6]. In addition, I will also discuss hybrid applications including the incorporation of NDs into glass to realise optical fibres that are intrinsically sensitive to magnetic fields [7], which is in contrast to conventional telecommunication-grade fibres.

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State independent uncertainty relations from eigenvalue minimization

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One of the very fundamental features of quantum physics is complementarity. The latter manifests itself in a ubiquitous way in all quantum physics and it is at the basis of various phenomena and applications, and therefore there are different "complementary" ways of quantifying it. A fundamental effect of complementarity is preparation uncertainty. The latter was first highlighted by Heisenberg in terms of its famous uncertainty relations, involving "products of variances" of two non-commuting operators. The latest development in this research framework have restated the problem in terms of the "sum of variances". This formulation of the task of quantifying preparation uncertainty allows on one hand to overcome some of the problems limiting the use of the product version. On the other hand it poses new challenges since the typical desired quantifier i.e., the state independent lower bound for the sum of variances l_b, is extremely difficult to evaluate in the general case i.e., for a set of N generic operators. This is especially true when the operators involved do not share any special relation e.g., symmetries. We show that a general answer to this problem can in fact be provided.
By means of a simple, yet powerful, mapping into an eigenvalue problem, we are able to devise a procedure allowing for the estimation of the searched lower bound l_b.In simple cases the method provides the exact value of l_b. When this is not possible, the method allows one:
1) to derive an approximation of l_b from below that itself constitutes a meaningful state independent lower bound; 2) to derive an approximation from above of l_b and the corresponding state that achieves such approximation; 3) the combination of 1) and 2) allows one to estimate the relative error involved of the approximation obtained. 4) the state determined with 2) allows one to identify a possible experimental implementation that approximately realizes the least uncertainty situation.
The method is general since it works for sum of variances involving a generic set of N operators. By applying the method to several relevant examples and we show that the approximation obtained is always very satisfactory. Indeed, the relative error with respect to the true known or numerically evaluated lower bound l_b is always, for the presented examples, of the order of few percentage points. While the main general results are stated for bounded operators, by means of a specific example we show that the method introduced can also be applied to unbounded operators.

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Machine Learning Applied to Quantum Synchronization-Assisted Probing

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A probing scheme is considered with an accessible and controllable qubit, used to probe an out-of equilibrium system consisting of a second qubit interacting with an environment. Quantum spontaneous synchronization between the probe and the system emerges in this model and, by tuning the probe frequency, can occur both in-phase and in anti-phase. The capability of machine learning in this probing scheme is analyzed based on quantum synchronization. An artificial neural network is used to infer, from a probe observable, main dissipation features, such as the environment Ohmicity index. The efficiency of the algorithm in the presence of some noise in the dataset is also considered. It is shown that the performance in either classification and regression is significantly improved due to the in/anti-phase synchronization transition. This opens the way to the characterization of environments with arbitrary spectral densities.

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Regularizing the variations of the environmental energy and the information flow via special initial correlations and spectral gaps

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In recent years, the vast research work on open quantum systems and quantum information processing has suggested various connections between the transfer of energy and the flow of quantum information. Backflow of energy can be observed in the non-Markovian regime, which can be interpreted as a flow of quantum information from the external environment back to the open system [1-4]. In local dephasing channels the qubit experiences pure dephasing and no dissipation of energy and the appearance of information backflow is related to the properties of the environmental spectrum [2,5]. The environmental energy can be manipulated by preparing the whole system in special correlated initial conditions. These special states are obtained from the thermal equilibrium of the whole system by performing a selective measure on the qubit [6]. If a spectral gap is created in the low-frequency distribution of bosonic modes and if the whole quantum system is prepared in the special correlated conditions the environmental energy exhibits regular damped oscillations around the asymptotic value. Damped oscillations with the same frequency describe the dephasing rate over long times for factorized initial conditions of the qubit and the external envronment, both at vanishing and non-vanishing temperature. The spectral gap induces and regularizes the oscillatory behaviors of the environmental energy and of the dephasing rate over long times. In fact, sequences of regular long-time intervals are found over which the environmental energy increases (decreases), for the special correlated initial conditions, and the open system looses (gains) information, for the factorized initial configurations, even at different temperatures. This relation is reversed in absence of the low-frequency gap, and can be lost if the spectral density is tailored near the upper cut-off frequency of the spectral gap as a power law with odd natural powers [7].

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Quantum Non-Locality in Networks

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Quantum non-locality, i.e. the violation of some Bell inequality, has proven to be an extremely useful concept in analyzing entanglement, quantum randomness and cryptography, among others. In particular, it led to the fascinating field of device-independent quantum information processing.

Historically, the idea was that the particles emitted by various quantum sources carry additional variables, known as hidden local variables. The more modern view, strongly influenced by computer cience, refers to these additional variables merely as shared randomness. This, however, leads to ambiguity when there is more than one source, as in quantum networks. Should the randomness produced by each source be considered as fully correlated, as in most common analyses, or should one analyze the situation assuming that each source produces independent randomness, closer to the historical spirit?

The latter is known, for the case of n independent sources, as n-locality. For example, in entanglement wapping there are two sources, hence “quantumness” should be analyzed using 2-locality (or, equivalently, bi-locality). The situation when the network has loops is especially interesting. Recent results for triangular networks will be presented.

Quantum trilateration of two particles and the role of photons in nanoscopy

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Optical microscopy is one of the most important tools for scientists in their quest to understand the natural world. Typically, optical microscopy only uses the wavelike properties of like, even most of the new techniques for super-resolution (sub-diffraction limit) imaging. The notable exception to this is quantum correlation microscopy (QCM) [1,2], where higher order correlations of the received intensity, via generalized Hanbury Brown and Twiss experiments, are combined to obtain imaging resolution that scales as $\sqrt{k}$, where k is the order of the correlations used. Although these higher order correlations provide information, the nature of this information is not always clear, and mapping the higher order correlations over a given scene provides may show little variation in the values. Here we show a minimal demonstration of the improvement provided by using quantum correlations, the quantum trilateration of two particles [3]. By considering two particles of unknown (but non-zero) brightness within a single diffraction limited spot, and only three measurement locations, we show that it is possible to resolve the particle location and relative brightness to arbitrary accuracy: a task impossible to achieve on the basis of classical intensity measurements alone. This example serves to highlight the power of quantum correlation microscopy and its role in improving microscopy.

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Cooling of Many-Body Systems via Selective Interactions

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Abstract

We propose a model describing N spin-1/2's coupled through N-order interaction terms, under local time-dependent fields. This model can be experimentally implemented with trapped ions and superconducting circuits current technologies. We succeed in exactly converting the quantum dynamics of this system into that of 2^{N-1} fictitious spin-1/2 dynamical problems. We show the possibility of generating GHZ states under specific time-dependent scenarios. Moreover, by appropriately engineering the time-dependence of the coupling parameters, one may choose a specific subspace in which the N-spin system dynamics takes place. This feature, called selective interaction, can generate a cooling effect of all N spins.

Trapped ions and superconducting circuits provide examples of quantum simulators of the dynamical be-haviour of other quantum systems. A fascinating formal aspect of quantum simulation is the mathematical occurrence of local N-wise spin-1/2 coupling terms in the Hamiltonian. Here N-wise means that the interaction among the N spins may be represented as an N-degree homogeneous multilinear polynomial in the 3N dynami-cal variables of all the N spins. Such a kind of coupling is of course alien to physical context like nuclear, atomic, and molecular physics. However, the usefulness of such N-spin Hamiltonian models has been recently brought to light in the treatment and the study of fermion lattice models where many-body interactions are present [1]. Moreover, the physical relevance of these couplings can be found in the fact that it is possible to implement such many-body interactions through both trapped ions- [2] and superconducting transmon qubit-based techniques [3], exploiting collective entangling operations [4].

We have exactly solved a time-dependent model of N spin-1/2 systems comprising highly non-local interactions, namely only the three uniform “diagonal” terms appear, that no term mixing different components of different spins is present in the Hamiltonian [5].

Firstly, we have shown that, thanks to non-local N-order interaction terms, it is possible to reverberate to all the spins in the system the dynamical effects generated in one of the N spins (ancilla qubit) by the application of a time-dependent field. This allows us to generate easily GHZ sates or a contemporary perfect inversion of all the spins. Secondly, we proposed a protocol through which we may generate a cooling effect of the whole spin system based on what we called selective interaction. The latter consists in the possibility to select a specific dynamically invariant subspace for a non-trivial dynamics of the N-spin system, by appropriately engineering the time-dependence of the coupling parameters. The key to get such physical results lies on the possibility to solve exactly the dynamics of the N-spin system by reducing the problem into a set of independent dynamical problems of single spin-1/2.

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Relativistic causality and quantum information – two perspectives.

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The most natural generalization of discrete quantum mechanical statistics were so called nosignaling (NS) boxes [1]. However it has been pointed that causality does not forbid some faster than light influences as long as they concern correlations and not local statistics [2]. We shall report the results of a systematic analysis of consequences of such influences which leads to a concept of relativistic causal (RC) boxes that goes far beyond that of the original NS ones [3]. The RC boxes may violate of the correlation monogamy relation and their framework entails redefinition of the concept of free will. Both aspects makes natural to pose questions about quantum-based security protocols in RC framework [4].

Independently of the above framework which considers point-like particles in space-time, the systematic analysis of the evolution of the continuous potential statistics of a single particle has been considered [5]. The previous formal condition [6] of causal evolution of such potential measure has been proven to be operational in the sense that its violations always leads to superluminal signaling. It has been accompanied by the complete study of its relation with three other axioms necessary to keep relativistic causality. All the results put limits on any future theory of evolution of an effective, potential statistics of klicks on detectors. Furthermore, they imply that non-relativiastic Schroedinger equation has built-in faster-than light signaling mechanism. Finally they prove a starting point to a possible framework of relativistic causal boxes with continuous variables which will be a subject of further research.

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Compressive Quantum Sensing

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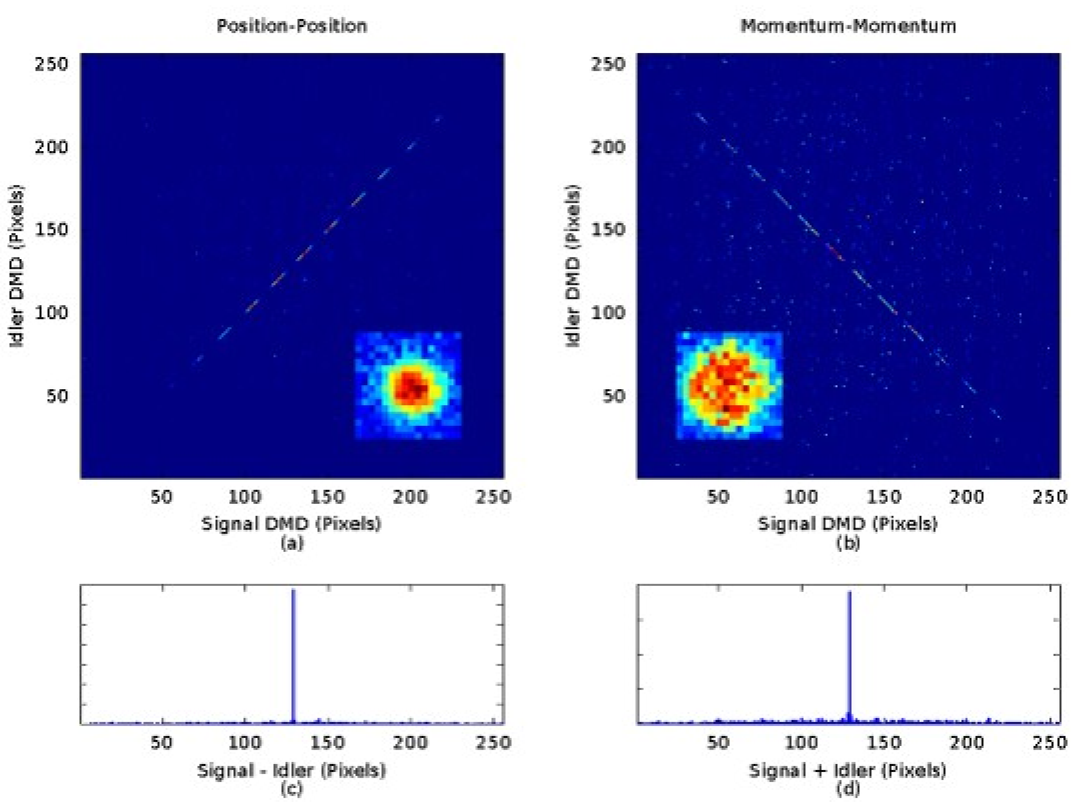
Compressive sensing utilizes sparsity to realize efficient image reconstruction. It is a valuable processing technique when cost, power, technology or computational overhead are limited or high. In the quantum domain technology usually limits efficient acquisition of weak or fragile signals. I will discuss the basics of information theory, compression, and compressive sensing. I will then discuss our recent work in compressive sensing. The topics of discussion include low-flux laser Radar, photonic phase transitions, high resolution biphoton ghost imaging, Ghost object tracking, 3D object tracking and high dimensional entanglement characterization. I will touch lightly on our current work of rapid wavefunction reconstruction and wavefront sensing. As an example (shown below), we were able efficiently and rapidly reconstruct high dimensional joint probability functions of biphotons in momentum and position. With conventional raster scanning this process would take approximately a year, but using double-pixel compressive sensing, the pictures were acquired in a few hours with modest flux.



Optical Resolution at the Quantum Fisher Information Limit

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There are many problems where optics and quantum theory overlap, one of them being the fundamental limit upon the resolution. The spatial resolution of any imaging device is restricted by diffraction, which causes a sharp point on the object to blur into a finite-sized spot in the image. This intrinsic blurring is encoded in the point-spread function, which hinders to distinguish two neighborhood points- an effect known as "Rayleigh curse". The same problem can be reconsidered from the perspective of quantum estimation theory, as done by Tsang and coworkers, see [Tsang:2016]. Here the constraints on resolution are more fundamental and correspond to the so called Fisher information and Cramer-Rao lower bound (CRLB) for parameter estimation.

When only light intensity at the image plane is measured on the basis of all the traditional techniques such as CCD detection, the Fisher information falls to zero as the separation between two sources decreases in accordance with Rayleigh curse. On the other hand, when the Fisher information is calculated for optimal measurement saturating the quantum Cramer-Rao Lower bound (qCRLB), it remains constant implying that the Rayleigh limit is subsidiary to the problem and super-resolution is in principle achievable see [Tsang:2016, Rehacek: 2017a].

The optimal measurements, on the contrary to the direct imaging, depends crucially on the number of parameters, which have to be estimated.

Multi-parameter quantum Cramér-Rao bound for simultaneously estimating the centroid, the separation, and the relative intensities of two incoherent optical point sources using a linear imaging system were addressed in [Rehacek: 2017b]. For equally bright sources, CRLB is independent of their separation as before. However, for the general case of unequally bright sources, the amount of information one can gain about the separation falls to zero, but we show that there is always a quadratic improvement in an optimal detection in comparison with the intensity measurements. This advantage can be of utmost importance in realistic scenarios, such as observational astronomy. Attainability of the qCRLB and feasibility of the multi-parameter estimation scheme was addressed in [Rehacek: 2018] . Estimation of 3 parameters requires at least 4 detected channels constructed from the projection into the superposition of the modes spanned by derivatives of the PSF.

Quantum-inspired imaging techniques can be extended to the time-frequency domain using mode-selective sum-frequency generation with shaped ultrafast pulses. Temporal and spectral separations between incoherent mixtures of single-photon level signals can be resolved up to level ten times smaller than their optical bandwidths yielding ten-fold improvement in precision over the intensity detection [Donohue: 2018].

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Coupling Germanium-Vacancy Centers in Diamond to a Fiber Based Micro Cavity

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Atomic size defects in diamond receive much attention because of their extraordinary optical and spin properties compared to other systems and platforms. The germanium vacancy (GeV) center has a narrow and ~6ns fast single photon emission spectrum with a zero-phonon line centered at 602 nm. The room temperature Debey-Waller factor was estimated to be ~0.26 [1], which together with a nuclear spin makes the GeV center an attractive candidate for applications in quantum cryptography and quantum information processing.

In this contribution, we report on the room temperature coupling of single GeV centers to a micrometer size high Finesse optical cavity. The cavity allows us to improve both the directional emission and the coherence by photon funneling [2]. Our cavity consists of a macroscopic flat mirror and a microscopic curved mirror made on the tip of a standard optical fiber to achieve a small cavity mode volume and coupling of the cavity to the single fiber mode. The GeV centers are obtained by ion implantation and annealing in a 1 μm thin diamond membrane placed on the flat mirror. By the aid of dielectric coatings and with the diamond inside the cavity, we obtain a cavity Finesse of the order of 10^4 at the transition wavelength of the GeV. By spectral characterization, we verify constructive interference of the longitudinal cavity mode inside the diamond membrane [3]. Although the total decay rate of single GeV centers remains unchanged inside the cavity, by comparing the GeV emission spectrum with and without the cavity we verify spectral enhancement and photon funneling of the GeV transition into the cavity mode [4]. Towards a fully coherent interface and addressing the GeV hyperfine transitions, the system is currently being implemented into a cryogenic environment.

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Evolution of Quantum Coherence of Two-Mode Gaussian Systems in a Thermal Environment

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An impressive progress in the development of quantum information theory is reached presently from the quantum resource theory approach to quantum correlations, like entanglement, discord and steering [1,2,3], and to quantum coherence.

Recently, a framework for the quantification of coherence has been established [4], in which quantum coherence is treated as a resource in a manner similar to quantum entanglement. In this work we address the quantification of coherence in Gaussian open systems [5], in the framework of the theory of open systems based on completely positive quantum dynamical semigroups.

We give a description of quantum coherence by using the relative entropy of coherence for a system consisting of two coupled non-resonant bosonic modes immersed in a thermal environment. We discuss the influence of the reservoir on the time evolution of the quantum coherence in terms of the covariance matrix for initial squeezed thermal states. We show that the dynamics of the quantum coherence strongly depends on the initial states of the subsystem (squeezing parameter and thermal photon numbers), the frequencies of the modes, the parameters characterizing the thermal reservoir (temperature and dissipation coefficient) and the intensity of the coupling between the two modes [6].

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Theoretical study of temporal quantum interference using a quantum fluxon with an internal degree of freedom

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Quantum mechanics predicts counterintuitive phenomena in microscopic scales. Spatial nonlocal effect demonstrated in double slit experiments is one such example. Recently, nonlocal effect in time domain is also discovered [1-4]. Quantum mechanics therefore seems to have succeeded in describing the physical phenomena of the *microscopic* world.

In contrast, there has been fundamental problems like "Schrödinger cat" whether quantum mechanics is applicable to the *macroscopic* world. Regarding the macroscopic spatial non-locality, interference fringes were demonstrated in a double slit experiment of a fullerene C_{60} [5]. As for the macroscopic temporal non-locality, we proposed a temporal double slit experiment using a quantum fluxon in the Josephson transmission line (JTL) and showed analytically quantum interference fringes of the fluxon in time domain [6].

Dissipation, which is caused by interactions with a large number of *internal* and/or external degrees of freedom, is inevitable and inherent in the macroscopic world. To include this peculiar phenomenon into our previous work, we investigate quantum interference of fluxon with internal degrees of freedom in time domain. In particular, we focus on the effect of internal degrees of freedom on interference of fluxon's center of mass. In general, both center of mass and internal motions cannot be observed simultaneously in quantum measurement. This is due to independent degrees of freedom. However, in temporal double slit experiment, two motion are connected by the same time parameter. Therefore, it can be possible to be observed them at the same time.

In this paper, we have derived analytically temporal interference effect of breather which is a fluxon and anti-fluxon pair in the JTL. As a result, we have found phase shift of the interference fringes depending on internal degrees of freedom in measurement of the center of mass coordinates of the breather. This preliminary result is effective for elucidation of dissipation from the temporal non-locality viewpoint on macroscopic scales.

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From single donor qubits in isotopically engineered silicon to a large scale quantum device

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Over the past decade we have investigated the properties of single qubits in devices formed from ion implanted ^{31}P donor atoms in enriched ^{28}Si substrates [1,2]. The enriched ^{28}Si substrate, depleted in ^{29}Si to below 0.1%, reduces qubit decoherence from donor electron spin coupling to the bath of spin-1/2 ^{29}Si nuclei originally present in natural silicon with 4.7% abundance. Detailed investigation of the remaining decoherence mechanisms, essential for understanding how to make a large-scale device, reveal the influence of the metal electrodes used for qubit control, the beneficial effect of strain and the role of uncontrolled tunneling of the electron from the host donor atom into the island of the single electron transistor used for qubit read-out. Appropriate mitigation strategies for these decohenrence mechanisms can lead to single donor electron T_1 times up to 9 s with a background magnetic field of 1 T and likewise long T_1 and T_2 times for the ^{31}P nuclear spin [3]. The recently proposed flip-flop qubit architecture [4] is suitable for a large-scale device that exploits these results with robust qubit entanglement over long distances up to several hundreds of nanometres and relaxes the generally tight constraints on the donor-qubit placement precision. The purpose of this paper is to review progress with the construction of such a large-scale device using the standard tools of the silicon information technology industry. To achieve this goal we have constructed a single ion implantation system that employs a nanostencil scanner [5] for sub-20 nm localization of the implanted ^{31}P donor atom qubits that is compatible with the engineering process flow for a full device. We have also developed an in-situ ^{28}Si enrichment process that does not depend on the supply of specialized enriched wafers. We compare our techniques to complementary approaches to the problem of precise localization of single donor atoms in silicon [6] that could allow the construction of large-scale quantum computer devices in the near term.

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On efficient methods of investigation of nonpositive maps

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The main aim of the presentation is to give an efficient procedure which allows Us to distinguish between positive and non-positive maps inside the set of all hermiticity preserving linear transformations. This procedure is important because we do not have any efficient method of characterizing positive maps which are not completely positive. The fundamental role in our considerations is played by the well-known in literature matrix CJ. We analyze signs of eigenvalues of this matrix for a given superoperator.

Coherent control of solid state nuclear spin nano-ensembles

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Detecting and controlling nuclear spin nano-ensembles is crucial for the further development of nuclear magnetic resonance (NMR) spectroscopy and for the emerging solid state quantum technology. Her we present the fabrication of a≈1 nanometer thick diamond layer consisting of13C nuclear spins doped with nitrogen-vacancy centres (NV) embedded in a spin-free 12C crystal matrix. A single NV in the vicinity of the layer is used for polarization of the 13C spins and the readout of their magnetization. We demonstrate a method for coherent control of few tens of nuclear spins by using radio frequency pulses, and show the basic coherent control experiments, Rabi oscillations and Ramsey spectroscopy, though any NMR pulse sequence can be implemented. The results shown here present an important step towards the realization of a nuclear spin based quantum simulator.

Measurement-device-independent verification of coherent channel extension

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Channel extension of a given quantum channel is a quantum broadcast channel[1] with one input system and two output systems, such that the given channel can be retrieved by discarding one of the output systems (say, bystander). If channel extension cannot be described as a convex sum of decomposition of a local subchannel and a local state, we call it a coherent extension. Along a similar line with entanglement verification in state extension, verification of channel extension can be categorized into two scenarios as follows. (1) If a bystander is trusted, we call it a coherent extension. (2) If a bystander is untrusted, we call it a channel steering[2].

In this research, we propose methods to verify coherence of the channel extension and channel steering in measurement-device-independent way. To do this, we first prove that using any bipartite pure state with full Schmidt rank, we can obtain two correspondences - 1. Coherent channel extension can be converted into CB/A tripartite entangled state, and *vice versa*. 2. Channel steering can be converted into CB/A steerable state, and *vice versa*. Therefore we convert the given channel extension to the tripartite state and verify its entanglement and steerability in measurement-device-independent way following the canonical methods proposed in Refs. [3,4]. These result in verification of coherent channel extension and steering. Furthermore, we analyzed the effect of imperfect preparation of bipartite full Schmidt rank pure state due to undesirable noise, and found that the threshold we can tolerate against arbitrary separable and unsteerable type of noise is given by robustness of entanglement and steering, introduced in Refs. [5,6]. Since measurement-device-independent verification has loss tolerant property, and a common form of noise in generating bipartite full Schmidt rank pure state is colored noise which is separable, we can overcome considerable amount of noise in a practical experimental situation.

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Optical coherence tomography, and other fundamental things, with a nonlinear interferometer

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In 1991 Zou et al. (Phys. Rev. Lett. **67**, 318, 1991) introduced the concept of induced coherence without induced emission. When signal photons (s_1 and s_2) emerging from two nonlinear crystals (SPDC) interfere, and the idler photons (i_1 and i_2) cannot provide any information about in which crystal the signal photons originated, there is first-order coherence between the signal photons. If some information exists, there is a loss of first-order coherence. This effect is still present in the case of strong pumping (Phys. Lett. A **166**, 303, 1992; **270**, 245, 2000).

Simple quantitative relationships of the form $D^2+V^2 < 1$ has been derived for the case of a single photon in an interferometer. D (distinguishability or predictability) is a measure of how much information is available about the path taken by the photons in the interferometer and V is the visibility of the interference. Here we introduce a new measure of distinguishability that applies to the weak and strong pumping regimes:

$$D = \sqrt{\frac{g^{(2)}_{s2,i3} - g^{(2)}_{s1,i3}}{g^{(2)}_{s2,i3} - 1}}$$

where $g^{(2)}_{ij}$ is the normalized second order-coherence function between signal and idler beam.

In 1991 Huang et al. (Science **254**, 1178, 1991) put forward the concept of Optical Coherence Tomography (OCT), an optical imaging technique that permits cross-sectional and axial high-resolution tomographic imaging of biological tissue. Barreto et al. (Nature **512**, 409, 2014) used the concept of induced coherence to demonstrate a 2D imaging system, where photons used to illuminate the object do not have to be detected at all. Here we go one step further and demonstrate in a proof-of-concept experiment (Phys. Rev A. **97**, 023824, 2018) that a nonlinear interferometer can be used to perform 3D imaging of a sample, i.e., in addition to obtaining information in the transverse plane (plane perpendicular to the beam), it can also provide optical sectioning of the sample (information in the axial direction, along the optical beam). In doing this, we put forward a new type of OCT scheme based however on a different physical principle: the varying reflectivity of the sample along the direction of propagation of the optical beam translates into changes of the degree of first-order coherence between two beams. As practical advantage, the scheme would allow deeper penetration into samples thanks to probing with longer wavelengths, while still using the optimum wavelength for detection. The scheme proposed can achieve sub-micron axial resolution by making use of nonlinear parametric sources with broad spectral bandwidth emission.

Simultaneous Correlations in mutually unbiased bases as resource for Quantum-information processing tasks

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A fundamental feature of quantum mechanics is the existence of mutually unbiased bases.The recently introduced measures of simultaneous correlations in mutually unbiased bases (SCMUB) inherent in the quantum state seek to quantify “quantumness” by the persistence of correlations in mutually unbiased bases used to measure the state [1,2]. Correlations in a given basis are quantified using the Holevo quantity, and comparing among incompatible bases their respective Holevo quantities, one can obtain a series of quantumness measures by choosing sets of bases that maximize the amount of simultaneous correlations.

In this report, we have shown how these particular measures of correlations can explain the efficiency of certain quantum mechanical tasks, namely, quantum steering [3] and remote state preparation [4].

In the context of Quantum Steering, considering Bell diagonal states we have shown suitable measures of simultaneous correlation in two and three mutually unbiased bases can be identified as the relevant resource in quantum steering quantitatively[3].

Similarly, in the context of Remote State Preparation such an appropriate measure of simultaneous correlations in three mutually unbiased bases can serve to quantify the usefulness of the resource for the RSP task using entangled as well as separable states [4].

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Entanglement-Assisted Communication in the Absence of Shared Reference Frames

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Almost any quantum information protocol, requires a shared reference frame between the two parties involved. Take for example the teleportation or the quantum key distribution. In the former, corrective operations of Bob will not produce the correct state if the reference frames are not aligned properly and in the latter, measurements of Bob along his own X and Z axes will not produce a key between him and Alice. Nevertheless, it is still possible to do classical and quantum communication by consuming more resources, e.g. sending more qubits [1]. It is also possible to encode information in those degrees of freedom which are invariant under rotation of coordinate systems, i.e. in the angle between two spins. We now ask if such a communication can be enhanced by encoding information in entangled states for two qubits. We begin by characterizing those parameters in a general state of two qubits which are invariant under rotations of reference frame and find three such parameters which can carry information to various degrees of efficiency [2]. The efficiency is measured by calculating the average information gain of Bob who carries optimal measurement to discover these values. In those cases which are comparable to product states, we see that entangled states are better carries of information than product states. We also ask if a prior entanglement can be a substitute for a shared reference frame and show that for certain quantum communication tasks a prior entanglement can do even better than a shared reference frame [3].

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Counterintuitive properties of the photon annihilation, applied to a thermal state of light: energy increasing and the quantum vampire effect

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Since quantum physics laws often contradict to our everyday experience, this science is really counterintuitive and full of paradoxes. Nevertheless, we try to use our intuition together with various analogies in order to understand some quantum phenomena. Sometimes it helps, but occasionally it leads to wrong statements.

In the current work we consider one of the most fundamental quantum operations: photon annihilation or subtraction. The basic property of the photon annihilation operator is that it decreases the number of photons in Fock states. So it is easy to represent the photon subtraction as some kind of nonlinear losses. This representation is intuitively obvious but completely wrong.

First, photon annihilation increases the mean photon number of any super-Poissonian state of light. Second, in contrast to the regular optical losses, photon subtraction, applied to a part of the light beam doesn’t change the beam profile (doesn’t cast a shadow). This is the basis of the “quantum vampire” effect [1].

We present an accurate theoretical explanation of both this effects and show their experimental implementation [2–4].

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Quantum walks under the continuous weak measurement

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Quantum walk is introduced as a quantum counterpart of the classical random walk and exhibits a number of non-classical features such as ballistic spreading and anti-bellshaped limit density [1] in making effective use of quantum phenomena like superposition and interference. In particular, the quadratically faster spreading of the wavepacket in position space compared to the classical random walks is useful for search and sampling algorithm like a Markov chain Monte Carlo (MCMC).

It has been devoted to study on their unique characteristics of quantum walks so far. But it is necessary for a desired purpose to obtain data by measurements at the final stage. Here we consider quantum measurement of quantum walks, especially continuous monitoring. As is well known, continuous (projective or strong) quantum measurement leads to freeze quantum state evolutions, so-called quantum Zeno effect [2]. Unfortunately, this spoils the favorable spread mentioned above. So it is required for other types of measurement schemes with great spread.

In this paper, we investigate the quantum evolution of a particle with a coin under the influence of continuous *weak* measurement in position subspace. Since weak measurement [3] admits amplification of outputs through state selections, it is expected to move a large distance beyond the classical one-step distance. In addition, the selected measurement is nothing but a projected measurement, resulting in the Zeno effect in continuous measurements. The measured state therefore freezes the state pinned at the amplified output (weak value). This causes anomalous spread in the position space. To show this, we formulate continuous weak measurement based on path integral formalism with the Kraus operator as a pointer operator with controllable interaction strengths covering from strong and weak interactions.

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Temporal Dynamics of Electrically Driven Single-Photon Sources Based on Color Centers in Diamond

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Color centers in diamond and related materials are now considered as the most promising candidates for single-photon sources (SPSs) for emerging quantum applications. From the practical point of view, operation under electrical excitation is more favorable than under optical excitation in terms of energy efficiency, integrability, and scalability. At the same time, the emission properties of electrically pumped color centers differ significantly from that of optically pumped, which can be clearly seen by measuring the $g^{(2)}$-function [1].

Here, using the developed theoretical framework [2–4], we study quantum correlation among photons emitted by electrically pumped NV centers in diamond. We perform self-consistent optoelectronic simulations of the single-photon emitting diamond diode and quantitatively reproduce recent measurements (Fig. 1). We show that both the dynamics of single-photon emission (SPE) and the SPE rate are fully determined only by the processes of electron and hole capture, which are typically significantly slower than the transitions among energy levels of the NV center. Surprisingly, the SPE dynamics is determined by the fastest of two capture processes, while the slowest capture process is responsible only for the SPE rate. We also closely investigate the transient response of the single-photon emitting diode. It appears that the response time of such an SPS approaches the inverse hole capture rate and can be easily less than 50 ns at high injection levels (Fig. 2). Thus, in spite of the relatively low maximum SPE rate (< 2 Mcps) [2–4], diamond SPSs can almost immediately respond on electrical excitation, which is crucial for building on-demand SPSs. Our findings give new insights into the photophysics of color centers in diamond and create the backbone for further research aiming at developing practical single-photon sources.

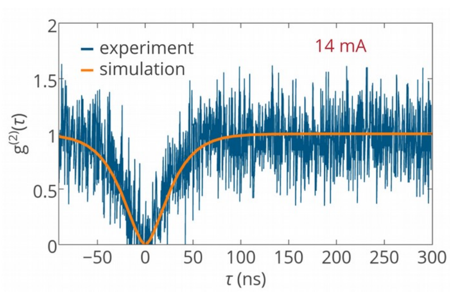

Fig. 1. Background corrected $g^{(2)}$ traces retrieved from the experiment [1] and predicted by our numerical simulations [3].

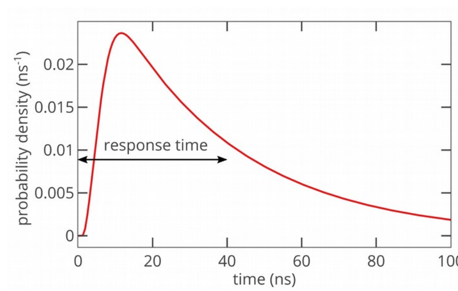

Fig. 2. Simulated probability of the first photon emission under pulsed excitation, the pulse duration is 13 ns.

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Direct quantum process tomography via measuring sequential weak values of incompatible observables

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Measurement plays a quintessential role in quantum theory and is tied to many peculiarities of quantum physics. Deeper understanding quantum measurement, therefore, is crucial in unraveling foundational problems in quantum theory as well as further developing quantum information technology. Typically, in quantum physics, we consider projection or von Neumann measurement and the projection postulate stipulates that a quantum system is irrecoverably collapsed into one of the eigenstates of the observable, resulting in maximum state disturbance. This then introduces impossibility of simultaneous measurement on incompatible or non-commuting observables.

A more general measurement, however, is allowed in quantum physics and, in this work, we consider so-called weak measurement. Weak measurement relaxes the aforementioned constraint and has enabled novel research into important problems in quantum physics and quantum information, e.g., minimum-disturbance measurement, relation between information gain and reversibility of measurement, protecting quantum states from decoherence, measurement-based quantum state manipulation, etc. In particular, the measurement outcome due to a weak measurement followed by a strong measurement, known as the weak value, is quite peculiar in that it is in general a complex number and is not bounded by the eigenvalue spectrum of the associated observable. The weak value, in addition to fundamental importance in quantum theory, has been shown to be important in quantum information, including precision measurement and metrology, direct characterization of quantum states, etc.

In this work, we report measurement of the weak value of two incompatible observables, termed as the sequential weak value. For the first time, we show the true quantum nature of the sequential weak value by making use of two-photon quantum interference so that the results can only be explained quantum physically. It is worth noting that optical weak value experiments to date are mostly classical in that the results can be fully explained with the classical electromagnetic theory, with few exceptions. Moreover, for the first time, we propose and demonstrate a novel direct quantum process tomography protocol via the sequential weak value measurement of two incompatible observables. Unlike the standard quantum process tomography technique, our direct quantum process tomography allows direct access to the process matrix elements, greatly simplifying the process of quantifying a quantum process or a quantum gate operation. We therefore expect that direct quantum process tomography will play an important role in wide-ranging subjects in quantum information research. Also, the genuine quantum nature of the sequential weak value for two incompatible observables reported in this work will be instrumental in rigorous tests quantum contextuality, macroscopic realism, uncertainty relations, measurement induced geometric phase, etc.

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Quantum Zeno effect in a PT symmetric optical system

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The conditions for parity-time (PT) invariance for an optical system composed of coupled cavities are obtained. Subsequently, the behavior of output intensity in both PT-symmetric and PT-symmetry-broken regimes are studied, and it is observed that photon numbers in the output increase exponentially in PT-symmetry-broken case for a set of input states. Specifically, we consider both pure and mixed input states and quantum states with both positive and negative Glauber Sudarshan P function, i.e., vacuum, coherent, NOON, and thermal state. Further, with the help of obtained photon numbers for different input states we study the feasibility of observing quantum Zeno and anti-Zeno effects in the system of interest. The observed quantum Zeno and anti-Zeno effects are found to be suppressed with a choice of parameters determining transition from the PT-symmetric to PT-symmetry-broken regime. The relative phase of input coherent fields is reported to play a significant role in the crossover between quantum Zeno and anti-Zeno effects for the same set of rest of the parameters. The study is further extended to observe some nonclassicality features witnessed by criteria based on number operators. In general, the dominance of the coupling strength between two cavities compared to the loss/gain rate in the field modes enhances the desired nonclassical features.

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Generation of optical-terahertz biphotons under strongly non-degenerate spontaneous parametric down-conversion

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We study the conditions for the generation of quantum-correlated pairs of photons belonging to extremely different spectral ranges, one of which is optical and the other is terahertz. Quantum states of this type could be useful for generation of entangled optical-terahertz states of electromagnetic field, construction of quantum single-photon sources at terahertz frequencies, quantum calibration of the terahertz wave sources and detectors, and other promising applications. Formally, such pairs can be produced in the process of parametric down-conversion (PDC) of the optical pump frequency ω_p, since the only one restriction is imposed on specific values of frequencies of signal (ω_s) and idler (ω_i) photons here, following from the energy conversation law $\hbar\omega_i + \hbar\omega_s = \hbar\omega_p$. In case of the strongly frequency non-degenerate PDC mode $\omega_i << \omega_s$, optical-terahertz biphotons can be emitted by a nonlinear medium. However, in comparison with the traditional optical biphotons, detection of correlation properties of the emitted photons encounters new particular challenges due to

- presence of classical thermal field fluctuations at THz frequencies,
- presence of inherent absorption of the nonlinear medium at THz frequencies,
- high angle diversity of the generated THz idler photons,
- current absence of THz single-photon detectors.

We show that the method of generalized Kirchhoff law, first formulated by Klyshko [1], enables to solve theoretical aspects of the problem. Expressions for specific frequency-angular distributions of photon numbers and power densities to be detected at signal and idler frequencies [2], as well as the corresponding second-order correlation functions, obtained for the low-gain spontaneous PDC regime, without paraxial approximations, taking the Gaussian pump beam profile, will be presented and discussed.

According to the theoretical predictions, account of both thermal fluctuations and intrinsic crystal absorption at THz frequencies make it difficult to achieve a high degree of correlation between optical and THz photons unless the crystal is cooled below ~10K. We have measured frequency-angular distributions of the power of signal photons generated in the Stokes and anti-Stokes ranges in the wide range of temperatures of the nonlinear bulk $Mg:LiNbO_3$ crystal, from 4 K up to 300 K. It is shown how the anti-Stokes signal reduces to zero at the lowest cryogenic temperatures, while in the anti-Stokes range the pure quantum contribution stays at all the temperatures. The temperature and spectral dependencies are analyzed with account of the crystal terahertz dispersion parameters, spectral behavior of the effective nonlinear coefficient, and thermal field fluctuations.

Possibility to measure the intensity of the terahertz idler waves generated via low-gain PDC is crucial for application of pairs of optical and terahertz photons. Our first experimental results on detection of the terahertz-frequency idler waves show that the lowest level of the parametric gain coefficient β, at which the weakest idler terahertz fluxes are still detectable by a sensitive hot-electron bolometer, correspond to the range $1 < \beta < 2.6$. Angular distribution of the terahertz idler photons and the dependence of their power on the pump intensity were measured by a hot-electron bolometer with a special design incorporating the $Mg:LiNbO_3$ crystal into a liquid Helium cooled chamber.

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Serial-parallel conversion for a stream of single photons using heralding signals

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To realize large scale photonic quantum technologies, it is important to use a source that emits multiple indistinguishable single photons. Until now, heralded single photon sources (HSPS) have been widely used because of the highly indistinguishable photons. Furthermore, a multiplexed HSPS has been demonstrated, which can maintain the probability of generating one photon while suppressing the probability of having more than two photons [1]. However, this scheme requires considerable resource overhead in terms of optical switches and HSPSs. To address this difficulty of constructing multiple single photon sources, a serial–parallel conversion method using heralding signals has been proposed by us, which can route a stream of *n* photons at successive intervals from a source to *n* different spatial modes.

In this talk, we report an experimental demonstration of the serial-parallel conversion for a stream of two photons from HSPS, as shown in Fig.1 [2]. Furthermore, we theoretically compared the conversion efficiency for *n* heralded photons with that for *n* unheralded photons and found that serial–parallel conversion for the heralded photon source could be more efficient than for the unheralded photon source. With the realized two-photon serial–parallel converter, we confirmed the efficacy of serial–parallel conversion for the case where a series of two heralding signals is detected. We achieved a conversion efficiency of 0.533±0.003, which exceeds the maximum achievable efficiency of 0.5 for serial–parallel conversion using unheralded photons and is double the efficiency (0.25) for that using beamsplitters. The efficiency of current setup can be increased up to 0.996 ±0.006 when the losses in the optical converter are corrected for.

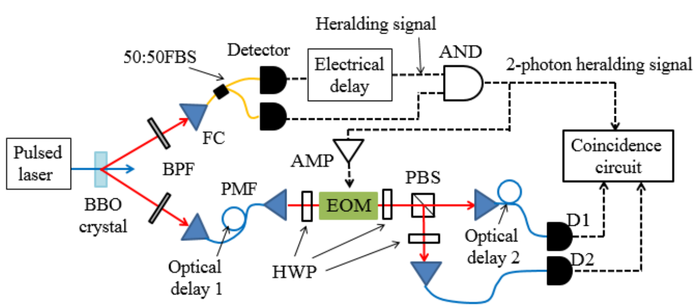

Fig.1: Experimental setup of serial-parallel convertor for *n* = 2.

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Generating maximal entanglement between spectrally distinct solid-state emitters

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(Dated: January 14, 2019)

We show [1] how to create maximal entanglement between two spectrally distinct solid-state emitters embedded in a waveguide Mach-Zehnder interferometer. By tailoring the input to the interferometer, we optimise the concurrence of the emitter qubits states and show that a two-photon input state can generate deterministic maximal entanglement even for emitters with significantly different transition energies and line-widths. The optimal frequency is determined by two competing processes: which-path erasure and interaction strength. Smaller spectral overlap can be overcome with higher photon numbers, and quasi-monochromatic photons are optimal for entanglement generation. Our work reveals a rich underlying structure in multi-photon scattering from two non-identical emitters, and provides a new methodology for solid-state entanglement generation, where the requirement for perfectly matched emitters can be relaxed in favour of optical state optimisation.

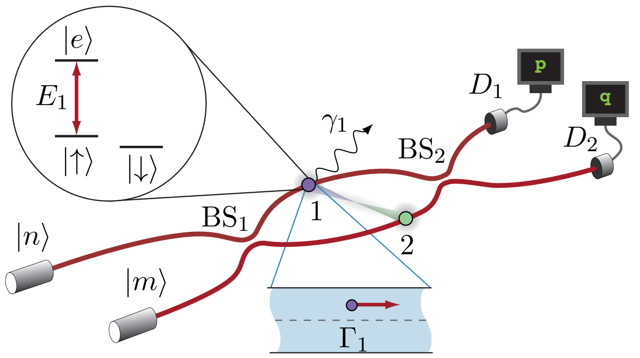

FIG. 1. Waveguide Mach-Zehnder interferometer with emitters embedded at positions 1 and 2, and with L-type level structures shown in the inset. The excited state $|e\rangle$ is coupled to a spin qubit state (e.g., $|\uparrow\rangle$) with transition energy E_α ($\alpha = 1, 2$), circular polarisation, and line-width Γ_α. The emitters are placed off-axis in the waveguide at c-points, such that circularly polarised light scatters only in the forward direction]2]. The loss rate from the guided mode is γ_α. Fock states $|n, m\rangle$ are injected into the interferometer, and detectors D_1 and D_2 record a photon number detector signature (p, q). Entangling techniques that use solid-state emitters are well-known to place very stringent requirements on the spectral identity of the emitters [3]. Our approach overcomes these restrictions by showing how to tailor multi-photon input states, mitigating a long considered weakness of solid-state emitters. We found that maximal deterministic entanglement between increasingly distinct emitters is possible using higher photon number input states $|n, m\rangle$, revealing a rich structure in multi-photon scattering from two emitters with different energies and line-widths (see Fig. 2).

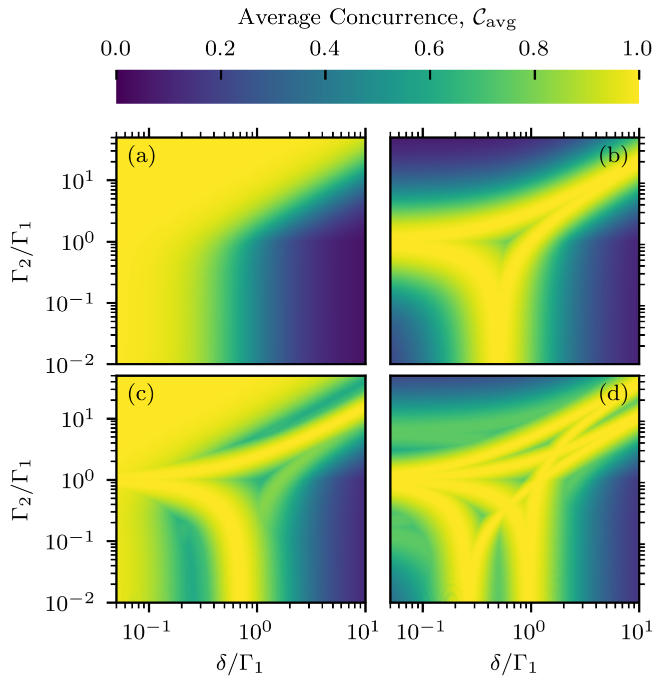

FIG. 2. Maximum average concurrence [4] for different photon input states injected into the interferometer. The emitter detuning δ and the line-width Γ_2 are both normalised to Γ_1, and we consider lossless waveguides. The input photons are identical and quasi-monochromatic in the configurations (a) $|n, m\rangle = |1, 0\rangle$; (b) $|1, 1\rangle$; (c) $|2, 1\rangle$; and (d) $|2, 2\rangle$. The characteristic shapes in (a) and (b) recur in (c) and (d), and are also found in higher photon number input states $|n, m\rangle$.

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Quantum-statistical and squeezing properties of the quantized cavity field interacting with laser cooled and trapped three-level radiator

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We study the interaction between three-level equidistant radiator (atom, molecule, quantum dot) and quantized cavity field. It is supposed that the dipole moment matrix transition elements between the adjacent atomic (molecular) levels may be different. In contrast with the micomaser model [1], in which atoms enter and leave the micromaser cavity in the same coherent state in present model three-level atom is laser cooled and trapped in the ground vibrational state in which mean vibrational number <n> is equal to zero [2], [3], [4] and [5].

It is supposed that at initial time t=0 the quantized cavity field is prepared in the Barut – Girardello coherent state. By using the operator functions method we have found exact analytical solution for the state-vector of the coupled atom-field system. By using this solution for the state-vector of atom-field system, the atomic population inversion, mean photon number and their fluctuations are examined as a function of time and initial atomic excitation. Much attention is also devoted to the higher-order squeezing properties of the quantized cavity field. In this situation, quantum-statistical properties and squeezing have the tendency towards oscillations, but the exact periodicity of these oscillations is violated by the analogy with the two-photon Jaynes-Cummings model [2].

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Quantum state engineering with twisted photons via adaptive shaping of the pump beam

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High-dimensional entanglement is a valuable resource for quantum communication, and photon pairs entangled in orbital angular momentum (OAM) are commonly used for encoding high-dimensional quantum states. However, methods for the preparation of maximally entangled states of arbitrary dimensionality are still lacking, and currently used approaches essentially rely on filtering and entanglement concentration [1].

We have experimentally realized a method for the generation of high-dimensional maximally entangled OAM states of photon pairs which does not require any of these procedures. Moreover, the prepared state is restricted to the subspace of the specified dimensionality, thus requiring minimal spatial postselection. The method we used is inspired by the theoretical work of Torres et al. [2], who showed that the amplitudes of the OAM-entangled quantum states can be controlled by nesting the phase singularities in the pump beam.

Following the idea of our previous experiment [3], we first minimized the spiral bandwidth by optimal pump beam focusing to concentrate the full flux of the down-converted photons in the low-order mode subspace. Then we reconfigured the OAM spectrum of the SPDC radiation by converting an initially Gaussian pump beam into a superposition of Laguerre-Gaussian modes. The careful adjustment of superposition coefficients allowed us to control both the weights and the phases of maximally entangled high-dimensional states.

As the result, we optimized the pump beam precisely for the generation of maximally entangled qutrits, ququarts and ququints using an adaptive algorithm [4]. The maximal entanglement between qutrits was verified by the violation of Collins-Gisin-Linden-Massar-Popescu (CGLMP) inequalities and full state tomography. According to our results, the adaptive procedure used in the experiment may be utilized to generate completely arbitrary spatial states of photon pairs, with the only limitation being the conservation laws in the SPDC process. As an example, we also generated non-maximally entangled pair of qutrits which violates the CGLMP inequality more strongly [5].

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Infrared Metrology with Visible Photons:Spectroscopy, Imaging, and Polarimetry

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Infrared (IR) optical range is important for material characterization and sensing because many materials have their distinctive IR absorption lines. Also, imaging in the IR range yields superior image contrast due to a significant reduction of scattering losses with the increase of the wavelength. This is why IR measurements are widely used in petrochemical, pharma, biomedical, homeland security, and other areas.

Even though there are many well-developed conventional methods for IR metrology, there are remaining challenges associated with high cost, low efficiency and stringent regulatory requirements for IR light sources and detectors. To mitigate these issues, we are developing new quantum-enabled techniques which allow us retrieving properties of materials in the IR range from the measurements of visible range photons with economical and efficient visible range devices.

The approach is based on the nonlinear interference of frequency correlated photons produced via spontaneous parametric down conversion (SPDC) [1, 2]. Within this process, one of the photons is generated in the detection-friendly visible range, and its correlated counterpart in the IR range is used to probe the properties of the medium. The nonlinear crystal is inserted in the Michelson-type interferometer, and the interference of visible photons is observed. Using rigorous quantum mechanical calculations, one can show that the visibility and phase of the observed fringes depend on the properties of the IR photon, which interacts with the sample. This allows us inferring the properties of the sample in the IR range from the measurements of visible range photons.

In a series of experiments, we demonstrate the IR absorption spectroscopy [1-3], tunable optical coherence tomography (OCT) [4], and polarimetry [5]. In all these demonstrations the IR properties (absorption spectra, refractive index, 3D images, and polarization) are inferred from the measurements of the interference pattern in the visible range thus making IR measurements much more affordable and straightforward.

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Realization and metrological characterization of absolute single-photon sources for quantum radiometry

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Single-photon sources play an important role in several fields of research and application, e.g. in quantum key distribution, quantum computing, and quantum-enhanced optical measurements. Compared to a classical source, a single-photon source is very favorable in radiometry as a standard source for the detection efficiency calibration of single-photon detectors. Furthermore, such source is necessary to close the gap between classical and quantum radiometry, i.e. for the direct comparison between classical analogue detectors and single-photon detectors, like e.g. the Si single-photon avalanche diode.

In the presentation, two approaches for the realization of a metrologically characterized, i.e. "absolute", single-photon source are reported on. One is based on a nitrogen-vacancy (NV-) center in nanodiamond. As reported in [1], this source is traceable to national standards for optical radiant power (cryogenic radiometer) and spectral power distribution (black body radiator) via an unbroken chain in terms of its absolute spectral photon flux per wavelength and its absolute spectral radiant flux per wavelength. This investigation includes a full determination of the measurement uncertainty [2]. Besides this, the angular emission behavior of such a NV-center in the vicinity of a dielectric is calculated. These results are compared to experimental results of the angle-dependent emission of a NV-center in nanodiamond.

Another promising candidate for the realization of an absolute single-photon source is an InGaAs/GaAs quantum dot embedded in a deterministic photonic structure. First results with respect to a full metrological characterization of this source are reported on. This includes the measurement of detector count rate, of the spectral and spatial emission characteristic as well as of the second-order correlation function. The spectral filtering is realized by two bandpass filters, each having a full width at half maximum of 0.5 nm and a transmission of about 90 %. The emission peak with the highest intensity is selected by filter rotation to adjust the central wavelength of the transmission window. In contrast to the standard filtering method with a monochromator, our method reduces the photon losses, thus resulting in high count rates combined with high single-photon purity.

Acknowledgement

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Can we save the quantum revolution?

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The consensus is that we are witnessing the dawn of the second quantum revolution. But will it live up to the great hopes it arouses? To help save it, there are aspects of the anticipated revolution that we should promote forcefully. Here is my perspective of it:

- Quantum teleportation: Existing teleportation of photons to other photons does not serve a truly useful purpose. Instead, we should target [1] teleportation of matter, e.g. molecules, via light [2] with the view of developing it into a novel method of hardware shipment without transporting it.

- Quantum entanglement distribution: Existing protocols are probabilistic and hence not fully reliable. Yet there are deterministic mechanisms mediated by long-range interactions that show promise[3].

- Quantum sensing: This is a promising direction, not only for physical but also for biomedical applications. MRI and NMR can be much improved by dynamical control of the probe [4] and by radically enhanced sample cooling.

- Quantum thermodynamic machines: Interest is growing in this field, but usually quantum machines are no better than classical ones. Still, quantum machines may achieve power boost ("quantum supremacy"), particularly via cooperativity of many atoms [9-12].

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Experimental Observation of Cooperative Absorption of Phase-Correlated Atoms

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Cooperative emission of phase-correlated atoms or superradiance has been observed in atomic cold ensembles, Bose-Einstein condensates and low-temperature solid-state systems. In superradiance, the emission intensity under ideal conditions is proportional to the square of a number of atoms, thus favorable for efficient quantum interfaces and advanced photonics. The Tavis-Cummings Hamiltonian accounting for superradiance also suggests cooperative absorption by phase-correlated atoms or superabsorption, which if realized would enable weak-signal sensing as well as efficient light-energy harvesting such as in photovoltaics and photosynthesis. However, the superabsorption has not been observed in experiments yet.

Here, we report experimental realization of superabsorption by using the time-reversed process of the superradiance. A nanohole array atomic beam aperture placed in front of a high-Q cavity makes it possible to localize the traversing two-level atoms in the cavity at desired positions. With a pump laser intersecting the atomic beam between the nanohole array and the cavity mode, we can prepare the individual atoms after going through the nanoholes in a superposition state of the ground and excited states with a prescribed phase. By employing a centered-square-lattice nanohole array with the hole spacing equal to the transition wavelength of the two-level atom (atomic barium with $^1S_0$ $^3P_1$ transition at 791nm), we can prepare every atom in the same superposition state. With this configuration, we have observed the coherent single-atom superradiance into the cavity mode [1], where atoms traversing the cavity in the cavity-field decay time cooperatively emit photons into the cavity mode although there is only one atom or less in the cavity, resulting in the cavity photon number growing proportional to . The time reversal was then achieved by preparing the phase of the superposition state of atoms opposite to that of the atoms which would generate the coherent superradiance with its phase the same as that of an input field. The intracavity field was depleted by the superabsorption much faster than by the ordinary absorption of ground-state atoms. We experimentally observed that the number of photons completely absorbed for a given time interval was nearly proportional to in contrast to the ordinary absorption proportional to , the number of atoms in the cavity. This dependence is a definitive evidence for superabsorption.

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Quantum Synchronization: From Squeezing to Other Applications

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Self-sustained oscillators are oscillators that do not require external forces to develop oscillations. However, the emergence of synchronization in quantum systems is widely explored. In a recent study, we showed that strong entrainment is possible if a self-sustained oscillator is coupled to a squeezing Hamiltonian, even if the squeezing. Moreover, we have shown how nanoscale heat engines are a natural platform to study quantum synchronization providing a possible link to quantum thermodynamics.

Fabrication of silicon-vacancy single-photon emitters at the electrostatic deflector line of the Tandem accelerator of LABEC (Florence)

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The pulsed beam line (DEFEL) of the 3 MeV Tandetron accelerator at LABEC (Florence)[1] has been upgraded for ion implantation experiments, aimed at the implementation of single-photon emitters in a diamond lattice. A wide range of implantation depths, down to 2.4 μm, has been investigated. We have obtained the shallower implantations either by lowering the accelerating voltage well below the lowest nominal value, or slowing down the beam particles by interposition of calibrated Al foils before the sample. A combination of slits and microscopic pin-holes, along with a piezo-motorized XY sample holder, allows both the implantation over large areas (~1mm^2) and the selection of smaller regions, down to the lateral straggling limit (~1mm^2). The electrostatic-deflector pulsing system allows implantations with fluences from 10^{15} cm^{-2} to a value as low as 10^7 cm^{-2}, used to reach the statistical single-ion regime, when fabricating matrices of emitters with micrometric resolution. A set-up for the activation of the implanted ions has been implemented, based on an annealing furnace, operating under controlled high-vacuum or reducing atmosphere (Ar+2%H_2) conditions. Silicon implantations have been performed in a variety of diamond samples (monocrystalline and polycrystalline plates, nano-crystalline membranes) and followed by annealing activation of negative Silicon-Vacancy (SiV^-) color centers. The photoluminescence properties of the SiV centers have been studied from room temperature, including their single-photon emission characteristics [2], to 861 K [3]. The photoluminescence signal was found to decrease only of a 50% and a 75% at 500 K and 700 K, respectively. In addition, we assessed the photostability of the center at least up to 861 K. Single-photon emitters have been obtained, exhibiting a short excited-state lifetime (~1 ns), a strong zero-phonon transition, with a narrow linewidth (~1.6 nm) and a very small inhomogeneous broadening (0.015 nm). These features qualify them for application in quantum optical technologies. The activation yield of the SiV centers has been assessed under different experimental conditions. It has been found to be independent of the implantation energy, its value being of the order of 3%, after annealing at around 1100 °C.

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Single-Pass Squeezing And Spatio-temporal Modes: Theoretical model and experimental characterization

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Single-pass squeezing is a deeply investigated quantum effect allowing for a measurement of the quantum noise reduction up to the single-pulse level [1]. Recent theoretical investigations show that the light generated by these sources is intrinsically multimode in the spatial and temporal domain [2]. Therefore, because of the recent improved technique in shaping the light in space and frequency, further theoretical and experimental analysis on these sources are of high interest.

Below-shot-noise fluctuations have been experimentally measured for several orthogonal spatial and temporal modes using optical parametric oscillators [3]. Conversely, in the single-pass case the temporal modes are coupled with the spatial ones.

In this work, we consider a complete spatio-temporal analysis of the process of down-conversion, with an approach similar to that in Ref. [4]. We found that the produced quantum state of light is a factorization of independently squeezed spatio-temporal modes, whose shape is skewed along a hyperbolic trajectory in the Fourier transform of the space-time (*i.e.*, the space defined by the transverse wave-vector and the frequency variables). An analytical solution of the problem allows to describe these modes as Hermite-Gaussian functions of a curvilinear spatio-temporal variable. Furthermore, we experimentally demonstrate the multimode nature of a type-I PDC source in both the spatial and the spectral domain from the same source using homodyne detection combined with an ultra-fast pulse-shaper.

This source has a wide variety of applications ranging from quantum metrology -due to its spatial and temporal multimode nature- to quantum computation -due to the single pass configuration allowing for the realization of time beam cluster states as in [5]. In addition, such source can be exploited to create a quantum complex network because of the rich entanglement structure in the frequency and transverse-vector space [6]. Finally, by exploiting a mode-tunable coherent single-photon subtractor on the generated quantum state [7], non-Gaussian networks can be realized giving rise to advantages for quantum computing.

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Optimality of Gaussian and non-Gaussian measurements for Gaussian metrology

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A central issue in quantum metrology is to find an optimal setup to measure a quantity with a precision beyond the standard quantum limit. This is usually assessed by the ability to reach the lower bound of the estimation error given an input state and a parameter-encoding process. Useful optical resources for metrology are Gaussian states and Gaussian measurements, both being experimentally available in a well-controlled and reliable manner. Questions of practical relevance and fundamental interest arise in context. Can Gaussian measurements achieve the ultimate bound in single-mode Gaussian metrology? If yes, what are the optimal Gaussian measurements setups? If no, what kind of non-Gaussian measurements are required and how can they be implemented in practice?

In this work, we identify three types of optimal Gaussian measurement setups yielding the maximal Fisher information depending on the type of probe state in single-mode Gaussian phase estimation. The homodyne measurement is shown to attain the ultimate bound for both displaced thermal probe states and squeezed vacuum probe states. For other Gaussian probe states, the optimized Gaussian measurements are not optimal although sometimes nearly optimal. For the latter, we demonstrate that the non-Gaussian measurement on the basis of the product quadrature operators $\hat{X}\hat{P}+\hat{P}\hat{X}$ is required for full optimality. We also prove the equivalence of optimal measurements between quantum Fisher information and quantum fidelity, enabling much simpler derivations to optimal positive-operator-valued-measurements for Gaussian metrology.

Experimental implementation of the above optimal non-Gaussian measurements seems quite challenging within current technology although they are in principle physical observables. Alternatively, we employ particular non-Gaussian measurements using the projection synthesis technique, where a set of projectors can be optimized by engineering an ancillary quantum state. We find that the optimized projectors lead to a larger Fisher information than those obtained by the optimal Gaussian measurements. To our knowledge, this is the first time when the projection synthesis is employed for quantum metrology. We thus expect this work will pave the way for various scenarios where optimal measurements are unknown.

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Efficient verification of Dicke states

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Quantum states with various kinds of entanglement are of central interests in quantum information processing tasks and foundational studies. Efficient verification of these states is a key in various applications. Recently, Pallister et al. [1] provided an optimal local measurement scheme for verifying general two-qubit pure states, as well as an efficient verification protocol for stabilizer states. Then, Zhu et al. [2] proposed an efficient method for verifying hypergraph states which requires only two distinct Pauli measurements for each party.

An interesting class of multipartite entangled states is the so-called Dicke states, which are relatively robust to decoherence and their permutation symmetry allows to simplify the process of tomography and entanglement characterization. Here, we propose an efficient method for verifying Dicke states [3], in which only two distinct Pauli measurements are needed. Our protocol proceeds in an adaptive way, and requires only $O(n/\epsilon)$ measurements with ϵ being the infidelity required. Hence, it is more efficient than all known strategies based on local measurements including tomography and direct fidelity estimation, and is comparable to the best nonlocal collective strategy. Moreover, Dicke states with thousands of qubits are able to be verified by our protocol.

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Detection efficiency calibration of InGaAs/InP single-photon detectors

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Single-photon avalanche diodes (SPAD) based on InGaAs/InP semiconductor materials are currently the most used detectors in many quantum technologies, such as quantum communication and quantum key distribution [1, 2]. The success of such technologies greatly depends on the performance of the detection system, i.e. on the parameters like the detection efficiency, the dead time, the afterpulsing and the dark counts of the single-photon detector used [3, 4]. The level of importance of each parameter depends on the detector type used, its operating conditions and the application itself. Strictly, the metrologically characterization of all these parameters is needed to fully guarantee the reliability of a quantum detection system. However, from the metrological, and specifically radiometric, point of view, the parameter that needs to be traceable to the primary standard for optical power (cryogenic radiometer) maintained by most of the National Metrology Institutes (NMIs) is the detection efficiency.

In this conference we will present the current results achieved on the calibration of the detection efficiency of gated and free-running InGaAs/InP SPAD detectors. This includes the detailed characterization of the different parameters that mainly affect the detection efficiency of the detector, such as dark counts, dead time and afterpulsing. A mathematical model including all these parameters to efficiently correct their influence on the detection efficiency will be introduced. Moreover, the setup and the reference standard used as well as a detailed estimation of the measurement uncertainty of the detection efficiency will be presented.

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Quantum enhanced correlated interferometry for Planck scale effects detection

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We demonstrate how the use of quantum light can offer advantages in an interferometric system composed by two Michelson interferometers. In particular, squeezing and bipartite correlations are considered. Each interferometer, of table-top scale, is working in power recycling configuration, close to the dark fringe, similarly to what is done in larger scale experiments such as the gravitational wave detectors [1] or the Fermilab ”Holometer” [2].

A faint correlated phase noise source acting in both the interferometers can emerge by performing the cross-correlation of their outputs in the time domain, or the cross- power spectral density (C-PSD) in the frequency domain, even if in the single interferometer that signal is completely hidden by the shot noise. This is the idea at the base of the Fermilab experiment [2], operating only with classical light.

Injecting squeezing independently in both the interferometers allows to improve the sensitivity of each of them, making possible to detect the presence of the correlated signals with significant reduction of the integration time [3,4]. The test white noise we injected and detected has an amplitude of half order of magnitude lower than the photon shot noise in each interferometer. In terms of absolute sensitivity, we have reached $3 \cdot 10^{-17} m/\sqrt{Hz}$ measured in a 100 kHz bandwidth around 13.5 MHz, which is 1/20 of the shot noise. We have achieved a quantum enhancement between 2.5 and 3 dB, this correspond to more than 3 times reduction of the integration time.

In a second phase, we exploit TWB-like quadrature correlation, demonstrating a noise reduction in their outputs subtraction. This scheme allows to detect uncorrelated signals otherwise hidden by the shot noise. This is the first time that quantum enhancement is demonstrated in a double interferometric scheme like this one.

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Anomalous weak values and contextuality: robustness, tightness, and imaginary parts [1]

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It has been shown that observations of weak values outside the eigenvalue range of the corresponding operator defy classical explanation in the sense of requiring contextuality [2]. Here we elaborate on and extend that result in several directions. Firstly, we provide ``robust" extensions that account for the failure of realistic postselections to be exactly projective and also allow for the weak measurement to be carried out with a qubit pointer in place of the traditional continuous system. Secondly, we show that all the operational constraints required by the argument are indeed necessary -- if any one of them is dropped, the anomaly can be reproduced classically. Finally, whereas the original result required the real part of the weak value to be anomalous, we also give a version for any weak value with an imaginary part. In short, we provide tight inequalities for witnessing nonclassicality using experimentally realistic measurements of any weak value that can be considered anomalous, clarify the debate surrounding them, and discuss the implications for recent experiments [3].

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Quantum Communication with Coherent States of Light

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Quantum Communication Protocols offer either qualitative advantages (Quantum Key Distribution) or quantitative advantages (Quantum Communication Protocols like Quantum Fingerprinting). We can realize such protocols resorting to tools that are readily available for implementation using simple tools like coherent states (laser pulses) and linear optics. Translation tools have been developed [1,7]. I will outline the different type of tasks that as a result can be translated this way, such as quantum fingerprinting [3,8], quantum scheduling [4], Quantum Retrieval Games [5]. Quantum Finger Printing has been realized [6] and has been shown to have quantum information complexity advantage [2]. This opens also the opportunity to explore topics in secure multi-party computation, which offers to balance privacy and security aspects in our word. I also report our investigations into Quantum Key Distribution that uses related tools [9]. Our goal is to drive research towards delivering protocols with a quantitative advantage that can be practically implemented and that address a real-world problem.

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Optimal entanglement witnesses from limited local measurements

Chiara Macchiavello

We address the problem of optimising entanglement witnesses when a limited fixed set of local measurements can be performed on a bipartite system, thus providing a procedure, feasible also for experiments, to detect entangled states using only the statistics of these local measurements. We completely characterize the class of entanglement witnesses that can be constructed from the measurements of bipartite Pauli operators in the case of two-qubit systems. In particular, we consider all possible extremal decomposable witnesses, which represent the most powerful form of witnesses for a two-qubit system, that can be defined from this set of measurements. We discuss possible extensions to higher dimension bipartite systems.

Quantum measurements of time

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We propose a time-of-arrival operator in quantum mechanics by conditioning on a quantum clock. This allows us to bypass the problems that afflict previous proposals, and to obtain a Hermitian time of arrival operator whose probability distribution arises from the Born rule and which has a clear physical interpretation. The same procedure can be employed to measure the "time at which some event happens" for arbitrary events (and not just specifically for the arrival time of a particle). This presentation is based on the theory presented here [1].

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Evolution of coherence properties of intense twinbeams

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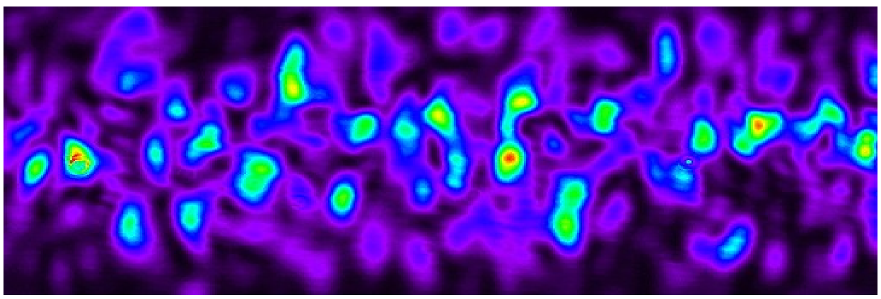

Spatial and spectral coherence of high-intensity twin beams generated in parametric fluorescence in the regime with pump depletion was experimentally investigated by means of intensity auto- and cross-correlation functions. Twin-beam coherence was studied from three different points of view. First, its dependence on the length of the crystal was addressed. Second, the influence of different radial emission angles on twin-beam coherence was analyzed. Third, the behavior of coherence as it depends on local intensity was investigated.

The initial growth of internal coherence with increasing twin-beam intensity followed by a decrease caused by strong pump depletion was experimentally observed both in wave-vector and spectrum domains. It was shown that the intensity at which the twinbeam reaches its coherence maxima depends on the configuration of the nonlinear interaction, including the crystal length, its orientation and radial emission angle. It was observed that it also depends on local twin-beam intensity. It was demonstrated that the intensity cross-correlation functions broaden significantly for higher pump powers and certain radial emission angles due to the anisotropy of the nonlinear crystal and to the non-collinear emission.

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Source side-channels in quantum cryptography

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Securing quantum cryptography against implementations loopholes is an ongoing effort by research labs, companies and standardization committees. I will brief on recent developments in loopholes in the sender equipment (photon source). These include practical attacks that induce an unexpected increase of source brightness, and attacks that rely on unintentional timing and spectral signatures of different source states.

Union bound for quantum information processing

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The union bound, alternatively known as Boole's inequality, represents one of the simplest yet non-trivial methods for bounding the probability that either one event or another occurs, in terms of the probabilities of the individual events. By induction, the bound applies to the union of multiple events, and it often provides a good enough bound in a variety of applications whenever the probabilities of the individual events are small relative to the number of events.

Recently, the union bound has been listed as the second step to try when attempting to 'upper-bound the probability of something bad', with the first step being to determine if the trivial bound of one is reasonable in a given application.

Generalizing the union bound to a quantum-mechanical set-up is non-trivial. A natural setting in which we would consider this generalization is when the goal is to bound the probability that two or more successive measurement outcomes do not occur. Clearly, if the projectors representing measurements do not commute, then classical reasoning does not apply and alternative methods are required.

Following [1] we report about a quantum union bound that is relevant when performing a sequence of binary outcome quantum measurements on a quantum state. It also involves a tunable parameter that can be optimized. The proof is rather elementary, relying only on basic properties of projectors, the Pythagorean theorem, and the Cauchy–Schwarz inequality.

Applications to a variety of situations, including quantum communication theory, quantum algorithms, quantum complexity theory and Hamiltonian complexity theory will be discussed.

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Quantum Suprematism and the Probability Distribution as an Alternative of the Wave Function and Density Matrix in Conventional Quantum Theory

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The probability representation of quantum states where the density matrices and state vectors are objectively mapped onto standard probability distributions [1-5] is reviewed. The examples of N-level atoms, especially the case of qubit states, are investigated. The triangle geometry of quantum states of qubits is studied and the bijective map of Bloch's sphere onto the triangles and squares (quantum suprematism picture) are discussed. The suprematism principle of states in quantum mechanics is formulated as the nonlinear addition rule for probability distributions identified with the qudit states. The Born rule is expressed as the nonlinear and nonlocal overlap of the probability distributions identified with quantum states. A proposal to check an analog of Bell's inequality for a single spin-1/2 state is presented.

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Quantum Model for Impulsive Stimulated Raman Scattering

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We present a fully-quantum theoretical model that we have recently developed for the description of Impulsive Stimulated Raman Scattering (ISRS) in the context of pump-probe experiments [1]. Unlike previous treatments discussed in the literature, our quantum model for the light-matter interaction allows to better understand and possibly exploit the role of "quantumness" of light in relevant experimental setups.

Some predictions of the quantum model are validated with pump-probe experiments performed on quartz. In particular, a first experiment is devoted to the measurement of transmittivity, that is modulated by the coherent excitation of phonons in the crystal. The second experiment instead deals with the reconstruction of the quadratures of the transmitted probe light, combining homodyne detection and pump-probe techniques. In both cases, we show that the model captures the essential features of the experimental outcomes.

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Inferences on Quantum Tomography of Time-Dependent Nonlinear Hamiltonian Systems

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Several models of nonlinear oscillators within the framework of a tomographic probability representation of quantum mechanics are discussed. The tomograms of the states satisfying the time dependent Schrödinger equation with the nonlinear Hamiltonians are obtained. The case of the quadratic Hamiltonian of the general form is considered in detail. Using the knowledge about the Green's function of such systems the time dependent tomogram is deduced and several examples of the quadratic Hamiltonian systems are studied in details. Next, the quasi-quadratic Hamiltonian systems are considered. In particular, the method given in [1,2] to introduce the tomogram for states whose Wigner function is a delta function is used. The cases of the coherent and the Fock bases defining the states are considered and the tomograms corresponding to these cases are studied.

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On the locality of the Aharonov-Bohm phase

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Aharonov and Bohm noted that a charge acquires a detectable phase when superposed along two paths enclosing an infinite solenoid, even though the charge's wave-function is non-zero exclusively where the solenoid's electric and magnetic fields are zero. This phase was long considered radically different from all other quantum phases, because it seems explainable only via local action of semiclassical potentials, not of the physical (gauge-invariant) electromagnetic fields. Recently Vaidman proposed a model explaining the phase only in terms of the electron's (magnetic) field at the solenoid, later developed by Kang with a lagrangian treatment. However, this analysis treats the field as semiclassical and is still not local. For it does not explain how the phase, generated at the solenoid, travels back to the charge where it is detectable. A quantum treatment is needed for that. In this paper we propose a local model, where the field is treated quantum-mechanically. This shows that the Aharonov-Bohm (AB) phase is generated by the same quantum local mechanism as all other electromagnetic phases. Namely, it is mediated by the entanglement between the superposed charge and the EM field, also modelled as a quantum system. Surprisingly, the quantised model produces experimentally different predictions from the semiclassical accounts of the AB phase, because it predicts that the phase at any point along the charge path is gauge-invariant and locally generated, and therefore in principle detectable. We also propose a realistic experiment, within current technological reach, where the predicted phase difference along the path is measured, by performing (a partial) quantum state tomography on the charge without closing the interfering charge paths.

Quantum States, Relative Entropies and Quantum Metrics, a Tomographic Reconstruction

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In the quantum version of information geometry, the monotonicity requirement on the quantum metric does not uniquely define the metric, unlike the classical case where, according to Centsov theorem, the metric is unique and is a multiple of the Fisher-Rao metric. On the other hand, tomography associates quantum states with fair probability distributions, tomograms. It is therefore puzzling that the “tomographic reconstruction” of quantum metrics starts from Fisher-Rao metric on the space of tomograms and reconstructs an infinity of alternative quantum metrics. We will show how this is possible in the case of quantum systems with a finite number of levels, i.e., q-dits. Our computations will be carried on in the framework of the geometrical description of quantum systems as “stratified manifolds”. In particular, this requires the development of a non-commutative differential calculus.

Sub shot noise measurements of transmission with each photon flux

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Optics is routinely used to measure physical parameters. Quantum mechanics describes how these different strategies are each limited in precision, as quantified by the resources used to perform each type of optical measurement. For example, the fundamental noise floor of optical measurements using a laser is Poisson-distributed and known as the shot noise limit. Application of quantum states of light can reduce noise for optical measurement (e.g. [1-4]). In this presentation, I will discuss methods that use correlated photon pair to surpass this limit in transmission estimation [1,4-6]. We will need to discuss how resources [7] can and are counted in experiments, the physical principles used and we will cover steps being taken to take the proof of principle post-selected experiments into practical use outside of the quantum optics laboratory. I will include in the presentation recent results from my group, including a new passive approach to clean noisy lasers to approach the shot noise limit [8] and recent demonstrations of sub shot noise absorption measurement using correlated photon pairs [9-11], detected with single photon detectors and correlated intensity measurement using scientific grade charge coupled device cameras (CCD). We will show combination of these techniques in a sub shot noise imaging demonstration.

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Quantum tennis-racket effect

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We study the quantum mechanical counterpart of tennis-racket effect in classical rigid body rotation. We find that, the instability of rotation around the intermediate axis induces an enhancement of the difference between quantum mechanical and classical ensemble dynamics. Due to the inherent nonlinearity, the quantum dynamics shows a dynamically generated interference pattern, which is lack classically even at the very early stage of time evolution. The whole scheme does not require any external interaction scheme, so it can unambiguously prove the quantum nature of the asymmetric top.

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Superconductivity in Degenerately-doped Si Nanowire Devices

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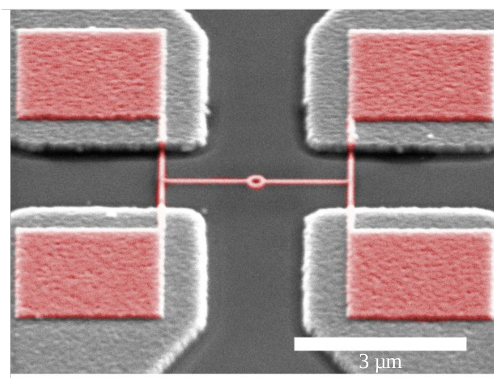

Fig. 1. The nanowire device structures: The false-colour indicates the degenerately-doped nanowire device structure including contact pads. The Al contacts (light grey) overlay the degenerately-doped contact pads. The etched wires have cross-sections of 50 × 50 nm^2. The inner radius of the ring shown here is 100 nm.

Magneto-transport measurements on degenerately-doped Si nanowire devices with nanoscale ring structures (Fig. 1) reveal periodic features that are consistent with fluxoid quantisation and the presence of a supercurrent in the ring when the device is cooled below the superconducting transition temperature of the Al contacts. The effect has been observed for nanowires degenerately doped both with B and with As. The devices were formed using ion implantation in silicon-on-insulator material with a 50 nm device layer. While superconductivity has previously been observed in B:Si, the B-concentration in our devices is a factor of 4-5 less than that at which superconductivity has previously been observed and as far as we are aware superconductivity has not previously been reported for As:Si. The observation of a superconducting transition in the entire device structure when it is cooled below the transition temperature of the Al is consistent with proximity-induced superconductivity in the degenerately-doped nanowire. While proximity-induced superconductivity has previously been observed in B:Si over length scales of the order of 10-100 nm the lateral scale of our devices is several micron. The observation of superconductivity in degenerately-doped Si nanowires on the length-scale of microns and for both n-Si and p-Si devices raises the possibility of exploring a range of superconducting phenomona in Si devices including fabrication of quantum-interference devices and sensors, superconducting resonators, and devices for research into generation of Majorana Fermions. In this presentation we will describe the device structures and present the magneto-transport data and discuss what we do and do not know about the origin of the superconductivity in our devices and describe possible future directions for our research.

Optimizing quantum enhanced imaging in realistic conditions

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Quantum correlations represent a fundamental tool for overcoming classical limits on precision of measurement. However, preserving these advantages in practical systems, where experimental imperfections are unavoidable, is a challenge of the utmost importance. Here we report our recent efforts in the measurement of the absorption coefficient of a faint object, analyzing the application of different measurement strategies and estimators by optimizing them in presence of optical losses and noise. We report, in a wide field sub-shot noise imaging experiment, the best sensitivity ever achieved in loss estimation without any kind of post selection [1].

By extending such optimization procedure to the measurement of the absorption pattern of a faint object we show a sensitivity improvement up to a factor 2 with respect to the simple protocol used in previous demonstrations [2]. In wide field sub-shot noise imaging there is a trade-off between the resolution and the sensitivity, due to the fact that pixels smaller than the characteristic size of the correlated spatial modes reduces the collection efficiency, deteriorating quantum correlations. Thus, in another way, the optimized protocol allows to significantly improve the resolution without giving up quantum advantage in the sensitivity.

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Status of the Leipzig diamond colour centre screening project

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The systematic screening of possible colour centres in diamond using ion implantation has already led to the discovery of many new centres [1] . The method uses shadow masks to create 20 µm implantation spots in a 3×3 mm² ultrapure diamond under different conditions. A sequence of thermal annealing and examination of the spots (using photoluminescence and spectroscopy) allows a fast screening of a large number of ions within one sample. To find ODMR active colour centers, we use a magnetic wide field dependent PL measurement as a first indication of whether a polarization take place and a coherent control of the spins is possible at all. The advantage of the wide field imaging technique is the possibility to inspect a large number of spots of color centers at the same time. Beside the search of new centres, we were able to investigate the formation properties of colour centers. This already led to new concepts to improve the creation yield of NV centers. The paper will discuss new colour centres with interesting properties like a coherent control of the spin state.

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Group covariant channels and testing extremality

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The most general form of evolution of a quantum state is described by a completely positive trace preserving (CPTP) map or a quantum channel. The set of CPTP maps is convex and determining the extreme points of this set is of importance from different aspects. The first trivial advantage of having the extreme points is that a general CPTP map can be described as a convex combination of extreme points which leads to characterizing the set of channels. Apart from the role of extreme points in characterizing CPTP maps, they have application in other areas such as simulation of quantum channels [1].

Explicit form of extreme points is known just for qubit channels [2] and going beyond qubit channels is challenging and at the same time essential to characterize qudit channels. One fundamental importance of going beyond qubit channel is to provide the possibility of having further investigations on Audenaert-Ruskai conjecture related to one of open problems in quantum information [3]. Despite all the efforts made, there is just partial success in understanding the properties of extreme points of qudit channel [4]. Here, we determine a subset of extreme points of CPTP maps for qutrit channels. Our strategy is o characterize the set of group covariant channels and then determine those group covariant channels which are extreme points. We develop an algorithmic approach with explicit pseudocode to construct group covariant channels for a given group (discrete finite groups or Lie groups) and testing whether they are extreme. By this method, we find families of extreme points of qutrit channels.

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Coupling-assisted Landau-Majorana-Stuckelberg-Zener transitions in two-interacting-qubit systems

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Abstract

We analyse a system of two interacting spin-qubits subjected to a Landau-Majorana-Stuckelberg-Zener (LMSZ) ramp. We show that LMSZ transitions of the two spin-qubits are possible without an external transverse static field thanks to the coupling between the spin-qubits. We show how such a physical effect could be exploited to estimate the strength of the interaction and to generate entangled states of the spins by appropriately setting the slope of the ramp. Moreover, effects of the coupling parameters on the time-behaviour of the Entanglement as well as effects stemming from the presence of a classical noise are analysed.

We considered [1] a physical system of two interacting spin-1/2's whose coupling consists in the anisotropic exchange interaction. Moreover, each of them is subjected to a local field linearly varying over time. The C_2-symmetry (with respect to the quantization axis z) possessed by the Hamiltonian allowed us to identify two independent single spin-1/2 sub-problems nested in the quantum dynamics of the two spin-qubits [2]. This fact gave us the possibility of decomposing the dynamical problem of the two spin-1/2's into two independent problems of single spin-1/2. In this way, our two-spin-qubit system may be regarded as a four-level system presenting an avoided crossing for each pair of instantaneous eigenenergies related to the two dynamically invariant subspaces. This aspect turned out to be the key to solve easily and exactly the dynamical problem, bringing to light several physically relevant aspects.

We showed that, although the absence of a transverse constant field, LMSZ transitions of the two spins are still possible. Such transitions occur thanks to the presence of the coupling between the spins which plays as effective static transverse field in each subdynamics.

Considering the STM (Scanning Tunneling Microscopy) scenario [3], that is when one local eld is applied on just one spin, we showed the possibility of 1) a non-local control, that is to manipulate the dynamics of one spin by applying the field on the other one and 2) a state exchange/transfer between the two spins. We brought to light how such effects are two different replies of the system depending on the isotropy properties of the exchange interaction.

It is worth the fact that each subdynamics is characterized by different combinations of the coupling parameters. Indeed, this aspect has relevant physical consequences since by studying the transition probability in the two subspaces, it is possible to estimate the strength of the interaction terms ruling the dynamics of the two-spin system. We brought to light how such an estimation could be of relevant interest since, through this knowledge, it is possible to set the slope of variation of the LMSZ ramp as to generate asymptotically entangled states of the two spin-1/2's. Moreover, we analysed the exact time-behaviour of the Entanglement for different initial conditions and how the coupling parameters can determine different Entanglement regimes and asymptotic values.

Finally, we emphasized how our symmetry-based analysis results useful also to get exact results when a classical random field component or non-Hermitian terms are considered to take into account the presence of a surrounding environment interacting with the system. In this cases, the dynamics decomposition is unaffected by the presence of the noise or the dephasing terms and then we may apply the results previously reported for a two-level system [4] and reread them in terms of the two spin-1/2's.

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Random Entanglement Witnesses for Gaussian States

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We study the efficiency of the entanglement detection in continuous variable systems by exploiting the concept of entanglement witness based on the covariance matrices. Given an unknown random bipartite Gaussian state we extract the information about the state through random homodyne measurements, from which the entanglement witnesses are constructed using the semidefinite programming technics [1].

We test the witness on the class of squeezed vacuum states, for which the entanglement is measured in terms of the squeezing present in the state. For this particular case, the less entanglement the easier it is detected than the higher entanglement, as it requires less measurements.

Concerning entanglement in randomly generated covariance matrices, the higher amount of entanglement present in the state facilitates its assessment with fewer measurements, which is similar to the case of the random entanglement witnesses acting on the state space [2]. In addition, as the set of entanglement witnesses for the second moments is fully characterized [3], we are also able to provide a witness for any entangled covariance matrix, including bound entanglement.

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Adversarial vs cooperative quantum estimation

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Parameter estimation, which plays a central role in mathematical statistics, becomes of tantamount importance in quantum information processing too [1]. A paradigmatic example is represented by the estimation of a parameter characterizing states transformations. These are ideally unitary transformations, however in practice one has to deal with noisy quantum maps, hence parameter estimation needs to be extended to quantum channels. It is well known that any quantum channel admits an isometry as a dilation [2]. Hence we can conceive the estimation of a family of isometries through quantum channels. This models a realistic situation where not all information concerning the measured systems is accessible. More precisely, given a one parameter family of isometries $V_\alpha^{A\to BF}$, we consider the parameter α's estimation by accessing only the system B [3]. This amounts to use the quantum channel between A and B of which $V_\alpha^{A\to BF}$ represents the Stinespring dilation. In this context different and interesting scenarios are considered. First, the system F is under control of a malicious being. Then the question arises of what are the conditions under which a legitimate user controlling the B system (besides A ones) can perform a better estimation. Second, the system F is under control of a benevolent helper. Then the question arises of what would be the advantage in estimating locally, but cooperatively the isometries. Here we address these issues by considering the mean square error (MSE) as figure of merit and pursuing its minimization. In one case we introduce the concept of private estimation, which amounts to the difference between the mean square error of the F system and of the B system. In the other case to constraint the possible measurements to be local in systems B and F we generalize the Personik's theorem [4]. Then, the effectiveness of these approaches to estimation is shown with an application to two-qubit unitaries, regarded as isometries by fixing one qubit input state.

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Making sense of the "energy resolution limit" in quantum sensing

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The quantum limits of sensing are usually discussed in terms of dimensionless quantities, for example $\delta\varphi \geq N^{-1/2}$ relates a phase uncertainty $\delta\varphi$ to the number N of (non-entangled) two-state systems used to measure it. In most real-world sensing problems, the quantities of interest have dimensions, e.g. length or time. To apply the well-known limits to such problems one needs also a scale factor, for example a wavelength or a frequency. These scale factors depend on the specific implementation of the measurement, e.g. which laser or atom is used.

In rather stark contrast to this, one can find references in the magnetic sensing literature to a "fundamental limit" on the "energy resolution per bandwidth" $E_R = \langle\delta B^2\rangle VT/2\mu_0 \geq \hbar$, where δB is the uncertainty in the magnetic field measurement, V is the volume over which the field is measured, and T is the measurement duration. The name reflects the fact that $\langle B^2\rangle V/2\mu_0$ is the magnetostatic energy in the volume. This alleged limit contains no scale factors apart from fundamental constants μ_0 and $\hbar$, and does not even mention the number of quanta N. It clearly cannot be reduced to known quantum limits.

We discuss the experimental and theoretical evidence for such a limit for magnetic sensing. This includes a wide survey of reported sensitivities, and known mechanisms to enforce it for sensor types including superconducting and hot vapour magnetometers. To this we add a mechanism to enforce an energy resolution limit in fixed, spatially-disordered spin-precession sensors (e.g. NV centres in diamond). Finally, we present experimental and theoretical evidence that spinor Bose-Einstein condensates, which are spin ensembles without spatial disorder, can surpass this limit.

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Electrical readout of coherently manipulated single NV diamond spin qubits at room temperature

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Important challenge in quantum technology is realisation of scalable quantum hardware for applications in quantum sensing, communication and computing. While the currently most studied systems operate at cryogenic temperatures, there are important applications for room temperature devices if quantum systems could be integrated with classical electronic peripheries and semiconductor compatible technologies.

Here we report on the construction of electrically read coherently driven single NV^- qubit operating at room temperature [1,2]. The results presented here demonstrate the potential of single NV centers and enable a simple and reliable implementation of quantum technology.

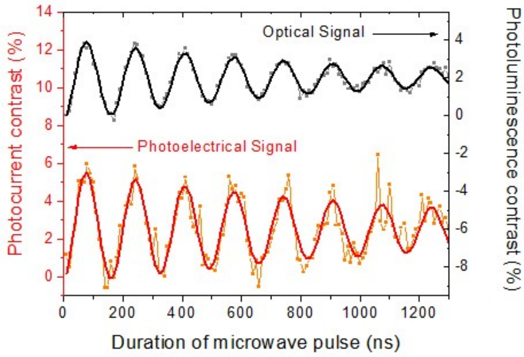

Figure 1 –Photoelectrical (bottom) and optical (top) detection of Rabi oscillations simultaneously performed on a single NV^- center in diamond (Laser illumination: 561 nm, 8 mW. Microwave power: 16 W). Symbols and fine lines: experimental data, Thick lines: fitting of experimental data.

The electrical qubit readout is based on photoionization of NV centres and subsequent detection of photocurrent, mirroring the spin-conserving optical transitions. The presented method offers advantages compared to conventional ODMR optical techniques, such as more than two orders of magnitude higher charge carriers detection rate, which does not saturate with the applied optical power. The qubit detection is not limited to the confocal resolution and it delivers a high signal contrast even in circumstances where confocal detection cannot provide it. We demonstrate the photoelectric readout of coherently driven single NV qubits, as shown in Fig. 1, following a method developed in our previous work[2] based on trains of laser (used for spin initialization and readout) and microwave (used for spin manipulation) pulses which are encoded into a low-frequency TTL envelope, provided as a reference to the lock-in amplifier used for photocurrent detection[3]. We discuss transport characteristics of diamond devices and their optimisation towards detection in the quantum regime. Finally we discuss the combination of lasers of different wavelengths to maximize the PDMR contrast.

Work was executed jointly with Peter Siyushev and Fedor Jelezko from the Institute of Quantum Optics University of Ulm and Emilie Bourgeois, Michal Gulka and Jaroslav Hruby from the University Hasselt.

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Recent Progress in Superconducting Nanowire Single Photon Detectors for QKD Applications

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We give an overview of recent progress in the field of superconducting nanowire single photon detectors, including the advent of time resolution below 10 ps Full Wave Half Maximum (FWHM). We discuss the potential to use this technology for ultra-high-clock rate quantum communication systems, enabling longer ranges and higher rates in quantum key distribution and quantum networks. We discuss the prospects for using this detector technology in future experiments.

Bell inequality in full field images of spontaneous parametric down-conversion.

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We use an imaging setup based on heralded imaging to test a Bell-CHSH inequality within images. Based on a single full-field image accumulated by a camera we find that the Bell inequality is violated.

Loophole free demonstrations of Bell non-locality have been performed recently. But testing Bell inequalities in new domains remains an objective of importance given the very pivotal role that Bell non-locality could play within the emergence of quantum technologies. We report here on an attempt at performing such a demonstration in the context of quantum imaging.

We perform an experimental realisation of the acquisition of full-field images that comprise a signature of a Bell type non-local behaviour. A spatially resolved BBO crystal is used to generate a bi-photon EPR state through the spontaneous parametric down conversion of a laser beam [1]. The two entangled photons are separated on a Beam-Spliter (BS) and we acquire full-field heralded images of spontaneous parametric down conversion (SPDC) filtered by phase objects placed on the path of each of the two photons. By recording heralded images [2] we ensure that the recorded images correspond to coincidence detection events.

In practical terms, the imaging scheme is implemented through an ICCD camera triggered by a single photon avalanche detector (SPAD). An image preserving delay line (~ 20 m long) is inserted in the imaging arm to compensate for the electronic trigger delay of the camera. By using different phase filters displayed on two SLMs that each interact with one of the two SPDC photons, we are able to perform a full set of projective measurements necessary to test Bell within a single image accumulated by the triggered camera. Through an analysis solely based on the data included in this image we are able to demonstrate the violation of a Bell-CHSH inequality [3]. The method can be seen as harnessing entanglement in the Orbital Angular Momentum (OAM) basis.

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Experiments for visualising time as an emergent property of quantum correlations

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The description of time in quantum mechanics and in particular in connection with quantum gravity and cosmology has always presented significant difficulties. One of descriptions based on Page and Wootters (PaW) mechanism which considers "time" as a quantum degree of freedom[1]. Here we give a complete review of the Page and Wootters' quantum time mechanism and provide experimental illustrations that are able to describe time as an emergent property of quantum correlations and giving us access to the possibility of a test of the Leggett-Garg inequalities.

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A quantum low-energy gravity model free from causality violation problems

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Wave-function collapse following a measurement process is a longstanding controversial issue of quantum physics. It introduces an element of strong non-linearity and irreversibility in an otherwise unitary and reversible dynamics. Several proposals of modification of Quantum Mechanics have been put forward in the past few decades in order to solve such a dichotomy. Among them, some approaches considered the possible role of gravity in the wave-function collapse as a result of the incompatibility of general relativity and unitary time evolution of Quantum Mechanics. In this contribution we present a nonunitary model of Newtonian Gravity (NNG) [1-3], which shows several appealing features: while reproducing at a macroscopic level the ordinary Newtonian interaction, it presents a mass threshold for gravitational localization. In particular, it provides a mechanism for the evolution of macroscopic coherent superpositions of states into ensembles of pure states.

In particular, we explicitly show how a one-parameter generalization of our NNG model is free from any causality-violation problem for any finite value of parameter [4]. The basic idea is to look at the single particle Newton-Schroedinger equation as the mean-field approximation of an equation of N identical copies of the particle, interacting via usual gravitational interaction, when N goes to infinity. The general N-copy model is a fully consistent quantum theory, in which superluminal communications are automatically avoided. This feature is shown to be a consequence of the intrinsic mechanism of spontaneous state reduction, built in in our NNG model and completely suppressed in the Newton-Schroedinger limit. We discuss in detail a specific (ideal) EPR-like experiment involving the superposition of two distinct Center of Mass position states of a massive body and show that the absence of causality violations leads to the appearance of unusual communications among Everett branches of the wave function. Our results agree with previous findings by Polchinski [5], obtained for a general class of nonlinear models characterized by nonlinear observables which depend only on the density matrix.

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Quantifying non-Markovianity: a quantum resource-theoretic approach

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The quantification and characterization of non-Markovian dynamics in quantum systems is an essential endeavor both for the theory of open quantum systems and for a deeper understanding of the effects of non-Markovian noise on quantum technologies. Here, we introduce the robustness of non-Markovianity, an operationally-motivated, *optimization-free* measure that quantifies the minimum amount of Markovian noise that can be mixed with a non-Markovian evolution before it becomes Markovian. We show that this quantity is a *bonafide* non-Markovianity measure, since it is faithful, convex, and monotonic under composition with Markovian channels. A two-fold operational interpretation of this measure is provided, with the robustness measure quantifying an advantage in both a state discrimination and a channel discrimination task. Moreover, we connect the robustness measure to single-shot information theory by using it to upper bound the min-accessible information of a non-Markovian map. Furthermore, we provide a closed-form analytical expression for this measure and show that, quite remarkably, the robustness measure is exactly equal to half the Rivas-Huelga-Plenio (RHP) measure [Phys. Rev. Lett. **105**, 050403 (2010)]. As a result, we provide a direct operational meaning to the RHP measure while endowing the robustness measure with the physical characterizations of the RHP measure.

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Mutually Unbiased Unitary Bases

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Analogous to Mutually Unbiased Bases (MUB) for [1] capturing the notion of equiprobable transition between states in one basis to another, is Mutually Unbiased Unitary Bases (MUUB) which, determines the equiprobable guesses of unitary transformations in one basis of M(,) comprising of unitary operators to another. MUUBs has in fact shown to be useful in specific quantum key distribution (QKD) protocols, namely bidirectional QKD protocols [2-4] akin to the role of MUBs for prepare and measure QKD schemes [5].

While ref. [6] gave the explicit construction for the maximal number of MUUBs for , for a and dimensional subspaces of M(,), little is known beyond that. In fact, for dimensional subspace of M(,), while it is known that the maximal numbers that MUUBs can have is [7], there is no known recipe for constructing the maximal number of such bases and it is not even known if such a number may even be achieved. It was also argued in ref. [6] that MUUBs cannot exist for non and dimensional subspaces of M(,) where is a prime number. We report about the case of dimensional subspace. Constructing monoids based on the underlying sets of and a subspace of M(,), an isomorphism between the monoids has led us to an important theorem of MUUB's construction for maximal number as being less than 1 compared to the MUBs for [8].

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The Principle of Spin-Spacetime Censorship

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Today, more than ever before, quantum entanglement and relativistic causality continue to be key concepts in theoretical works that seek to unify quantum mechanics and gravity. In this work, we show that the interplay between relativistic causality and quantum entanglement has intriguing consequences on the spacetime surrounding elementary particles with spin. General relativity predicts that a spin-generated magnetic dipole field causes a (slight) bending to the spacetime around particles, breaking the spherical symmetry of spacetime. However, through a gedanken experiment analyzed in the context of quantum information, we show that such a spin-related deviation from spherical symmetry would violate the “no-signaling” principle, leading to a conflict between causality and entanglement. To avoid this conundrum, the measurable spacetime around the particle's rest frame must be spherically symmetric. This way, we show that there must be an additional principle, classical or quantum, which constitutes a censorship mechanism, compensating for the spacetime bending due to spin or preventing the possibility of spacetime-based spin detection. We wish to achieve a physical understanding of such a mechanism. This may shed a new light on the interface between quantum mechanics and general relativity.

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Optimal nanoscale quantum sensor-devices based on individual color centers in diamond

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Nitrogen vacancy (NV) color centers in diamond are versatile sensors due to their stable photoluminescence (PL), optically readable spin and high coherence time even at room temperature. NV centers form multifunctional sensors that simultaneously detect magnetic fields and optical near fields, the latter via energy transfer processes [1].

To reach high spatial resolution down to the nanoscale and to investigate samples with non-flat geometry, we incorporate NV centers into tip-like, single-crystal diamond nanostructures: Our diamond scanning probes consist of diamond nanopillars fabricated on thin (< 1 μm) platforms which we attach to tuning forks for controlled scanning close to the sample surface [see Fig. 1(a)+(b)]. Simultaneously, our optimized diamond nanopillars, which resemble the shape of truncated cones, serve as waveguides efficiently channeling the NV center's PL [see Fig. 1(c)] [2]. We summarize our latest results on fabricating diamond scanning probes as well as roads towards up-scaling of the fabrication via using novel, large-scale, single-crystal diamond material [3].

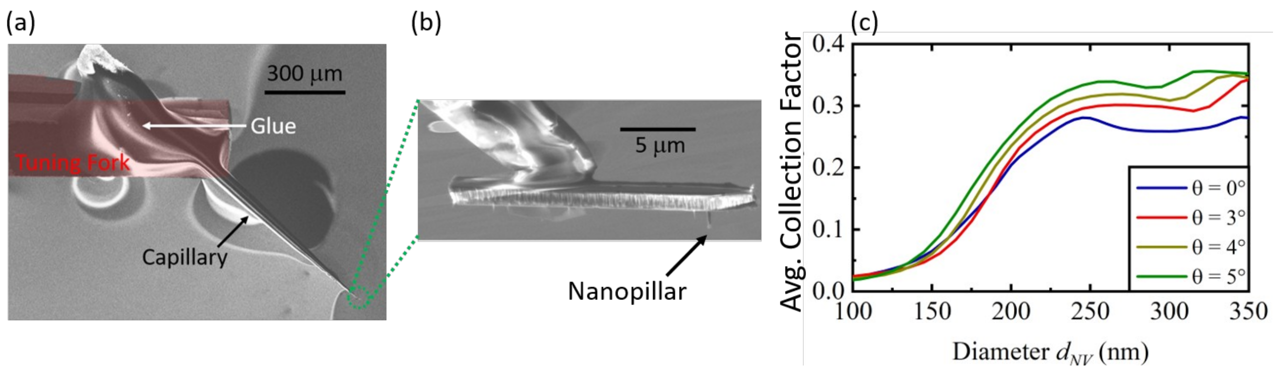

Figure 1: (a)+(b) Electron microscopy images of a diamond scanning probe: (a) illustrates our approach to controlled scanning of the diamond device via mounting to a tuning fork as oscillator via a capillary as a holder. (b) close-up of the scanning probe device consisting of a nanopillar on a holding platform. (c) Results from FDTD simulations of diamond nanopillars (length 1 μm). The shape of the pillar is a truncated cone (smaller Diameter facet contains NV center) with a sidewall angle θ. The averaged collection factor indicates the PL rate collectible from a single NV center [2].

To obtain nanoscale resolution, NV centers must be created shallowly (< 10 nm) below the diamond's surface. This might lead to charge state instabilities and lowers the spin coherence of shallow NV centers. We investigate wet chemical fluorine treatments of the diamond surface as well as approaches towards low damage etching of diamond. To demonstrate the potential of color centers as multifunctional sensors, we demonstrate quenching of NV PL via depositing graphene onto the diamond surface. Moreover, we investigate the interaction of luminescent WSe_2 flakes transferred onto diamond nanopillars. We discuss potential applications of our sensor devices especially for applications connected to the life sciences e.g. for investigating magnetic composite particles.

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Ptychographic reconstruction of pure quantum states and its optical implementation

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Ptychography is an imaging technique where a localized illumination scans overlapping regions of an object and generates a set of diffraction intensities used to computationally reconstruct its complex-valued transmission function [1]. We introduce a quantum analogue of this technique designed to reconstruct d-dimensional pure states. A set of n rank-r projectors "scans" overlapping parts of an input state and the moduli of the d Fourier amplitudes of each part are measured. These nd outcomes are fed into an iterative phase retrieval algorithm which successfully estimates the state [2]. Unlike traditional approaches to state reconstruction [3–5], the ptychographic scheme uses a single measurement basis; the diversity and redundancy in the measured data – key for its success – are provided by the overlapping projections. For d up to 21, r=floor(d/2), and considering an economic (n=4) and a costly (n=d) scenario, we present experimental results for the ptychographic reconstruction of pure quantum states encoded in the transverse spatial modes of an optical field using a phase-only programmable spatial light modulator. Finally, we discuss the possible extensions of quantum ptychography for continuous variables, mixed states and processes.

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Bohmian mechanics for instrumentalists

Hrvoje Nikolic

Bohmian mechanics (BM) is usually presented as a theory the main point of which is to offer a fundamental microscopic ontology - trajectories of elementary particles. For many physicists, especially instrumentalists, such a point of departure may not look intuitive and well-motivated, the consequence of which is that BM is widely ignored or misunderstood in a wider physics community. In this talk I offer a new instrumentalist-friendly formulation of BM in which the main objects of concern are macroscopic phenomena, especially readings of the measuring instruments, while microscopic ontology only plays a secondary auxiliary role. With such a reformulation it is much easier to understand intuitively why BM always makes the same measurable predictions as standard quantum mechanics (QM), irrespective of the details of microscopic ontology. Furthermore, from the point of view that all currently well-established physical theories are merely effective theories describing only the phenomena at sufficiently large distances, it seems plausible to assume that relativistic quantum field theory (QFT) must be replaced by a completely different theory at smaller distances. Analogy with condensed-matter physics suggests that this more fundamental theory could have a form of non-relativistic QM, which offers a simple generic resolution of an apparent conflict between BM and relativistic QFT.

Spatial characterization of photonic polarization entanglement over large distances

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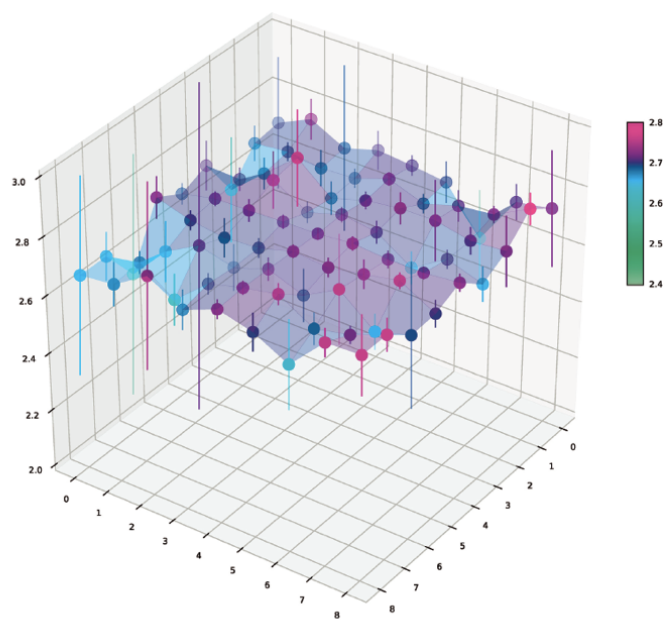
Scalable technologies to characterize the performance of quantum devices are important for creating large, distributed quantum systems. Chief among the resources of quantum information processing is entanglement. Here we describe the full temporal and spatial characterization of polarization-entangled photons produced by Spontaneous Parametric Down Conversions using an intensified fast optical camera, Tpx3Cam, with nanosecond time resolution. This novel technique allows for precise determination of Bell inequality parameters, as well as novel characterization methods of the spatial distribution of entangled quantum information. This could lead to multiple applications in Quantum Information Science, opening new perspectives for the scalability of quantum experiments. In particular, it is suitable to characterize the performance of many quantum devices simultaneously, which is crucial to create large quantum networks and quantum processing units. The figure below from the predecessor study [1] shows spatial distribution in (x,y) for the Clauser-Horne-Shimony-Holt (CHSH) inequality violation presented as the resulting S -values (z-axis).



Our new studies presented here extend the results to the long-distance distribution of the entanglement over conventional single-mode fibers. We study dependence of the coincidence rate of entangled photons as determined by the fast camera as function of photon polarization for separations of several kilometers. Our results represent the first time that the ideas of quantum entanglement, as used in the well known Bell inequality violation protocols, are combined with fast, high-resolution quantum imaging, which is able to time-stamp the photon pairs with MHz rates over long distances.

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Bell vs. Galileo: the proof of the inequality clashes with the principle of relativity

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The Bell's theorem stands as an insuperable roadblock in the path to a very desired intuitive solution of the Einstein-Podolsky-Rosen paradox and, hence, it lies at the core of the current lack of a clear interpretation of the quantum formalism. The theorem states through an experimentally testable inequality that the predictions of quantum mechanics for the Bell's polarization states of two entangled particles cannot be reproduced by any statistical model of hidden variables that shares certain intuitive features. The proof of the inequality, however, implicitly assumes a preferred frame of reference in which the orientations of the two detectors can be independently described: the proof does not hold when the experiments are described taking the orientation of one of the detectors as a reference direction. This observation suggests that the Bell's theorem can be overcome if the global rotational symmetry is spontaneously broken by the hidden configurations of the pair of entangled particles. Following this observation we build an explicit local model of hidden variables that reproduces the predictions of quantum mechanics for the Bell's states.

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Position-Selective Silicon Vacancy Formation in Silicon Carbide Devices using Proton Beam Writing

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Silicon vacancy (V_{Si}) in silicon carbide (SiC) is regarded as a key element for quantum sensing since spin in V_{Si} can be manipulated at room temperature and its spin states can be identified from optically detected magnetic resonance (ODMR) [1,2]. For the establishment of quantum sensing based on V_{Si} in SiC, it is necessary to develop the technology for its creation, *e.g.* position and concentration. Especially, SiC quantum sensors which consist of V_{Si}s embedded in SiC electronic devices are expected since the fabrication process of SiC electronic devices has been developed. In this case, it is very important to introduce V_{Si}s in SiC devices without the degradation of device performance.

Proton beam writing (PBW) is know as direct lithography technique using focused micro-ion-beams of MeV protons [3]. In our previous study, we demonstrate the creation of V_{Si}s in certain locations of SiC pn diodes using PBW. Also, we observed electroluminescence (EL) from V_{Si}s in SiC diodes as well as their photoluminescence (PL) [4].

In this study, we create V_{Si}s in certain locations of SiC diodes using PBW, and investigate relationship between PL/EL intensities from V_{Si}s and amounts of irradiated protons. We also demonstrate quantum sensing such as magnetic field using ODMR for V_{Si}s introduced by PBW.

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Non-phase matched spontaneous parametric down conversion: generation of states with huge spatial entanglement

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Over the past century, many 'fundamental' limits imposed by classical laws have been surpassed by the application of quantum physics. Specifically, it is quantum entanglement that plays a role in beating many of the classical limits. In quantum optics spontaneous parametric down conversion (SPDC) is often used as source of entangled photons. In SPDC a single pump photon spontaneously decays into two entangled daughter photons (signal and idler). The daughter photons can be entangled with respect to many different variables, for example: frequency, polarization and photon number.

Here we consider the degree of entanglement between the signal and idler wavevectors. The wavevector correlations are strongly dependent on the geometry of the non-linear crystal in which the daughter photons are generated. By using a lightly focused pump beam, which maintains the transverse correlations between the signal and idler photons, and a micro-scale layer of lithium niobate, which dramatically broadens the longitudinal correlations, we observe huge entanglement. By working with such a thin layer of lithium niobate, the need to satisfy momentum conservation between the pump and daughter photons is alleviated. This, to our knowledge, is the first time SPDC has been observed without phase matching.

To measure the wavevector entanglement two methods were used: the direct measurement of the spatial distribution of photon correlations [1] and stimulated emission tomography [2]. The first measurement was performed by placing two spatial light modulators (SLMs) in the signal and idler beam paths and by selecting a specific phase mask on each SLM the joint spectral intensity of the photon correlations was found using a Hanbury Brown-Twiss set up. The second measurement involved using a seed beam, whose incidence angle could be tuned, to stimulate the idler beam. By measuring the spatial distribution of the macroscopic idler beam as a function of the seed beam angle, we could reconstruct the JSI. The measured degree of entanglement was R=6400 using the Fedorov ratio, however we anticipate this value can exceed $R=10^5$ by changing the pump beam waist.

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Phase-shift-keyed binary communication in noisy channels: when squeezing can help

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We address binary phase-shift-keyed communication based on Gaussian states and prove that squeezing can enhance optical state discrimination at fixed channel energy. By investigating the ultimate bounds to discrimination (the Helstrom bound), we show that displaced-squeezed states (DDS) can be better discriminated than coherent states (CS) if the squeezing fraction (the ratio between the squeezed photons and the total energy of the signal) is below a given threshold. When phase noise affects the propagation of the signals, the performance of the DDS with a homodyne receiver can beat the Helstrom bound for CS. Furthermore, we find that as the phase noise increases, the protocol exploiting DDS and homodyning becomes nearly-optimal, i.e. approaches the corresponding Helstrom bound. Finally, we consider imperfections in the preparation of the seed signal (the state before the encoding). As one may expect, the presence of a not pure seed state increases the discrimination error probability; nevertheless, we still find that squeezing may improve state discrimination with respect to the protocol based on CS.

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Toward Quantum Enhanced Schlieren Imaging of Refractive Object

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The technological exploitation of quantum states and quantum correlations is one of the most active research frontier nowadays. Quantum metrology aims at the improvement of the resolution or the sensitivity of measurements, beating fundamental limits found in the classical framework.

The most fundamental limit to the sensitivity in every optical measurement, when classical states of light are considered, is the “Shot Noise Limit” (SNL). Quantum mechanics allows the existence of states with strong degree of cooperation among photons, which can be produced and manipulated experimentally, to surpass the SNL.

In this work, we develop a phenomenological model to evaluate the possible quantum enhancement in detecting objects with a non-uniform refractive spatial profile. A sensible improvement on the classical accuracy is shown to be found when the "Twin Beam State" (TWB) is used. One of the created beams is used to probe the sample and the other as a reference. The distortion of the light rays, due to the object, is measured by comparing the intensity pattern detected in the probe branch with the unperturbed profile detected in the reference branch. Such a scheme allows exploiting the quantum correlation of the two beams to reduce the fluctuations. In particular, the multimode spatial correlation, naturally produced in the Parametric Down Conversion (PDC) process, allows a 2D reconstruction of complex spatial profiles, thus enabling an enhanced imaging. More in general, this approach can be applied to wave front distortion measurements.

The preliminary results reported here are the basis for a forthcoming experimental demonstration of this enhanced measurement scheme.

Automated quantum operations and simulation in photonic qutrits

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We develop an experimental optical setup capable of implementing a class of quantum operations in photonics qutrit states in transverse Gaussian paths variables. In order to implement a projection operation is necessary to be able, in principle, to transform an initial state that can be an one-component state in a superposition of the others base states. The setup that implements the operations needs to transform one photonic path state in a state of D paths at the apparatus exit. Such transformation is difficult to be realized for photonic slit states.

We present an experimental implementation of projection and permutation operations using a photonic qutrit encoded in transverse Gaussian path states. Such experimental setup allows to obtain a qutrit state at the apparatus exit making them useful for a sequential quantum operation. The present operations are implemented exploring the diffraction of a Gaussian beam by a SLM due to a periodic phase modulation in it. We identify one set of diffraction phase grating for each operation realized, so the experiment is automated in the sense the operations are changed just by changing the SLM phase grating by a computer. Recent results show the possibility of using the optical setup for simulating quantum open systems: three level systems with quantum jumps between the levels.

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Experimental Quantum-Enhanced Magnetometry Using a Superconducting Circuit

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Superconducting circuits represent a promising platform for implementing quantum information protocols, with significant effort in recent years directed toward the development of quantum processors. We show [1] that these circuits can be used for enhanced quantum sensing, by employing phase estimation algorithms. We modify and implement two such algorithms, the Kitaev and the semiclassical Fourier-transform, to achieve the detection of a magnetic field below the standard quantum limit and approaching the Heisenberg scaling. Both protocols utilize a uses Bayesian inference subroutine, where the results of a single measurement are used to decide the parameters of the next measurement.

The experiment [1] demonstrates the potential of these quantum devices to outperform classical magnetic field detectors. This method can be extended to multi-dimensional Hilbert spaces, where we design a specific protocol for the case of an artificial three-level system [2].

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Universal Quantum Magnetometry with Spin States at Equilibrium

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We address metrological protocols for the estimation of the intensity and the orientation of a magnetic field, and show that quantum-enhanced precision may be achieved by probing the field with an arbitrary spin at thermal equilibrium. A general expression is derived for the ultimate achievable precision, as given by the quantum Fisher information. The optimal observable is shown to correspond to the spin projection along a temperature-dependent direction, and allows a maximally precise parameter estimation also through ensemble measurements. Finally, we prove the robustness of our scheme against deviations of the measured spin projection from optimality.

Nonclassicality and secure quantum communication

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It's well-known that to avail any advantage of quantum computation or communication one needs to exploit nonclassical feature(s) of one or more quantum states. A nonclassical state is usually characterized by the negative values of Glauber-Sudarshan P function, which also implies non-Zero quantum coherence in the coherent state basis. Keeping this in mind, we begin with the comparative studies of measures of (a) nonclassicality [1] and (b) quantum coherence [2], and thus identify a set of nonclassical states which can be of use in secure quantum communication. We show a set of experimentally realizable physical systems which may be used to realize these nonclassical states [3-5]. Subsequently, we discuss the role of these nonclassical states in the implementation of the schemes of continuous variable quantum communication and discrete variable quantum communication. Specifically, for the protocols of quantum key distribution, quantum dialogue, and controlled quantum dialogue. A few protocols designed by us [6] are presented briefly to illustrate the advantages and issues associated with the protocols continuous variable quantum communication in comparison with the discrete variable protocols designed for performing the same task. Finally, optical designs for the implementation of the schemes proposed by us have also been presented.

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On nanodiamonds for matter-wave interferometry

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I will present a novel protocol for the generation of macroscopic superpositions of spatially separated states of a nanodiamond hosting an NV center. The interaction of a magnetic field gradient with the NV center exerts a spin-dependent force that leads to a splitting of the spatial wave function of the diamond along the dimension of the gradient. However, due to the presence of diamagnetic forces acting on the diamond, the separation distance of the two superposed components of the wave function is limited to a maximum. We introduce a pulse sequence acting on the NV center that magnifies the separation, making it grow linearly in time. Remarkably, our pulse sequence can also protect the coherence of the superposition from harmful experimental imperfections like misalignments of the setup with the gravitational field, interactions of the diamond with stray static electric fields or the interaction of the net magnetic moment of the diamond with the magnetic field gradient. Additionally, I will analyze the role played by the rotational degrees of freedom of the diamond and discuss on the effect of spin flips from the dangling bonds at the surface of the diamond as well as that of Casimir-Polder forces arising between the diamond and the magnets.

Quantum Key Distribution Networks

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Quantum Key Distribution (QKD) is a cryptographic primitive, i.e. a basic protocol. It is the most prominent representative of the class of Quantum Communication protocols. QKD ensures key agreement between two remote parties (traditionally named Alice and Bob). The key itself has the highest possible security, known as Information Theoretic Security – ITS. Alice and Bob are connected by a Quantum Channel that is the crucial element of the QKD link between them. Fundamentally, distant ITS key agreement will not be feasible, if the world would be classical, as QKD is a direct consequence of Quantum Mechanics. For the same reason, however, the functional length of the Quantum Channel between Alice and Bob, i.e. the distance of operation of the QKD link, is restricted – to let us say less than 150 km for practical present-day components and at reasonable (not extremely low) rates. Without going into technical details, this comes as a consequence of decoherence, i.e. deterioration of the Quantum Channel quality below some critical value, if it exceeds a certain length. Already very early after the invention of QKD it became clear that this range is not sufficient for practical applicability, except in some very rare cases.

This was the basic motivation for putting forward the concept and then the initial realizations of the so called QKD Networks [1]. The first intuition had been: try to apply QKD to extend the distance of ITS key generation. Naturally, Quantum Mechanics has been the first direction to look at. The introduction of Quantum Repeaters, allows conceptually to piece together several QKD links by a specific quantum regeneration, to form arbitrarily long Quantum channels and hence ensure ITS key generation across continental or global scales. Unfortunately Quantum Repeaters are yet to be developed to a level suitable for practical realization. Researchers had to (initially?) resort to simpler solutions that replace Quantum Repeaters by trust assumptions. The so called Trusted Repeater QKD Networks (TRQKDNs) replace a Quantum Repeater by a trusted QKD Node – a secure location, in which very roughly speaking the ITS key is regenerated and resent.

TRQKDN have found a wide proliferation in experiments and demonstrations [2,3]. Besides distributing key at longer distances these have also enabled typical networking capabilities such as any-to-any and even multiparty key generation, load balancing and even Quality of Service. These efforts have remained, however, restricted to the quantum-physics research community and little attention from practical stakeholders has been shown. In the last few years the situation finally started to change. After more than a decade of TRQKDNs, telecommunication companies start to show initial interest. Simultaneously, basically from the user side, a novel and, from a practical point of view, revolutionary paradigm change is underway. While, as discussed, the initial idea has been to seek QKD-like but network-wide ITS key distribution that in turn can be used for a multitude of security applications, today increasingly this paradigm is reversed to a new approach focusing on the question: how to use QKD to increase the security of telecommunication networks, in which end-to-end key distribution can but must not necessarily be used.

This talk aims at presenting the discussed paradigm shift to the Quantum Technology community. We hope that a better mutual understanding will emerge in the future and allow a fruitful cooperation of quantum and telecommunication experts so that QKD and Quantum Communication at large can finally find broader proliferation and gain in practical significance.

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New perspectives in Correlation Plenoptic Imaging

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We present the recent advances in Correlation Plenoptic Imaging (CPI), a technique based on intensity correlation measurement that enables to perform the typical tasks of plenoptic imaging [1], such as refocusing, change of point of view and distance detection, without entailing the loss of spatial resolution, which is unavoidable in plenoptic devices based on ordinary intensity measurements. In CPI, spatial and directional information are encoded by performing correlation measurements on two separate sensors, this enables reaching an unprecedented combination of resolution and depth of field. In the first proposed scheme of CPI [2], the image of the object was reproduced on one sensor by lensless ghost imaging, while information on the direction of light was acquired by imaging the focusing element, through an ordinary lens, on the second sensor. This scheme provided the basis for the first experimental demonstration of CPI with chaotic light [3]. Here, we present novel schemes optimizing the noise performances of CPI and adapting it to new imaging scenarios, such as microscopy.

We first discuss a different configuration of CPI with chaotic light, involving a conceptual inversion between ordinary imaging, now used to image of the object, and ghost imaging, employed to image the focusing element [4]. Besides the possibility to combine plenoptic imaging and high-resolution standard imaging in the same device, we shall also show that the new scheme provides relevant improvement in terms of signal-to-noise ratio [5]. We shall also present a more advanced CPI scheme, in which two generic planes in the surrounding of the object are imaged by a single lens on two disjoint sensors. The second development that we present consists in the application of CPI to microscopy. It is worth recalling that the typical loss of resolution in state-of-the-art devices hindered the direct application of plenoptic imaging to microscopy, which became feasible only after the development of deconvolution algorithms to partially recover resolution [6,7]. In Correlation Plenoptic Microscopy (CPM), the sample is considered as a source of chaotic light [8], and correlation measurement enables to reconstruct the direction of light from the sample to the objective. CPM will be shown to cover a much wider range of applicability than the previously developed CPI setups, where directional reconstruction is not effective in presence of both randomly emitting/scattering samples, and turbulence effects close to the sample. Finally, we describe the working principle and imaging properties of CPI setups illuminated by entangled photon pairs generated by spontaneous parametric down conversion [9], illustrating the advantages in terms of signal-to-noise ratio.

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Reconstruction of joint photon-number distributions of twin beams incorporating spatial noise reduction

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A new method for reconstructing joint photon-number distributions of twin beams from the experimental photocount histograms measured by photon-number-resolving detectors with spatial resolution (iCCD, EMCCD cameras) is suggested and experimentally implemented. The information about positions of individual photocounts on the photocathode is exploited for noise reduction based on spatial pairing of photons. This allows for additional noise reduction compared to the standard reconstruction methods. Superior performance of the developed method above the usual one applying the maximum-likelihood approach is demonstrated. Non-classicality depths related to several non-classicality indicators based on the integrated-intensity moments are successfully applied to monitor the performance of the developed method in reducing the noise. They help to choose optimal parameters for the best performance of the method.

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Hybrid quantum photonics

Alberto Peruzzo

We review recent progress and new opportunities for scaling up quantum optical technology via hybrid integration of single photon emitters and detectors with integrated photonic circuits.

From Unitary to Open Quantum Walks: generalization and unification

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Open quantum walks (OQWs)[1] were introduced as quantum analogs to classical Markov chains. In contrast to unitary quantum walks[2], OQWs are driven by the dissipative interaction with the environment and are formulated in the language of open quantum systems[3]. OQWs demonstrates rich dynamical behaviour[1,4] and can be used to perform efficient dissipative quantum computation and state engineering[5]. Another benefit of OQWs is in the well-defined classical limit[6]. The unitary quantum walks are gaining computational power from the quantum interference between the nodes of a walk and the asymptotic behavior of them is highly non-gaussian[2].

In this talk, we will introduce a generalization of the QWs, which includes OQWs and unitary quantum walks as limiting cases. In this generalization one can naturally identify an order parameter ξ = (characteristic time)/(characteristic length) and perform characteristic length a "thermodynamic" limit in the characteristic parameters, while keeping ξ a constant. As the result, the asymptotic distribution of the position of the walker for the small values of ξ corresponds to a unitary quantum walk and for the large values of ξ to an OQWs, respectively.

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Non-Gaussian quantum state tomography and engineering using photon-number resolved detection

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Quantum pure states with non-Gaussian (i.e., non-positive) Wigner functions are crucial to universal, fault-tolerant quantum computing with continuous variables (CV), as they both condition the quantum-computing exponential speedup given by the Gottesman-Knill theorem for qumodes, as well as the ability to do CV entanglement distillation and quantum error correction. Examples of relevant non-Gaussian states are Fock states, cat states, and Gottesman-Kitaev-Preskill (GKP) error encoding. A convenient way of generating non-Gaussian states is the projection onto Fock states that results from photon-number-resolving measurements. I will present our recent results on quantum tomography of a single-photon Fock state using superconducting transition-edge sensors, as well as the extension of this experiment to the squeezing-free quantum preparation of displaced single-photon states, cat states, and GKP states.

Experimental realization of robust weak measurements

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Ever since their initial proposal, weak values [1] have given rise to much controversy [2-5]. Despite of practical and conceptual achievements made possible using weak values [6-12], they have been criticized [13-15] because of their statistical nature and the need to employ large ensembles of particles for inferring them. Their ``anomalous'' nature (i.e. their possibility of showing values out of the measured observable eigenvalues range) was also debated, as well as their quantumness.

In this work we address all of these issues by presenting the first experiment able to observe anomalous weak values with just a single photon detection. Such framework reproduces in a much more faithful way the original idea, with each outcome (anomalous or not) no longer arising from a statistical analysis.

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ANALYSIS OF THE EXPERIMENTS DEMONSTRATING QUANTUM PIGEONHOLE PARADOX

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We critically analyze recent experiments [1,2] demonstrating the failure of the pigeonhole principle in the framework of quantum mechanics as described in [3]. In this example three particles (pigeons) are pre and post-selected in particular states in two holes such that no two particles are in the same hole. Demonstration of such a failure should consist of
a) creating of particular pre and post-selected states of three particles;
b) strong measurement of every (one) particular pair showing that the particles are not in the same hole;
c) simultaneous weak measurement of all pairs showing for each pair that the particles are not in the same hole.
We find however, that the experiments do not achieve all these challenges.

- No weak measurement of all pairs, simultaneously showing that bipartite interactions disappear, has been performed.
- The role of the pigeon holes played polarization states of particles. These are essentially spin states which have no classical analog for single particles.
- In experiment [1], instead of pre and post-selction of the states corresponding to the failure of the pigeonhole principle, it was shown that when particles are in the same hole (have the same polarization) the particulr post-selection does not happen, so it is only an indirect demonstration.
- In [1], a polarization beam splitter served as a nondemolition measurement of identical photon polarization. The mechanism relies strongly on the fact that the particles were identical (same color photons). But the example [3] was defined for distinguishable particles, so [1], strictly speaking, was not demonstration of [3].
- In [2], the correct pre and postselected states of the particles were created. However, the experiment (weak measurement of polarization) was performed not on three, not on two, but just on a single particle. The weak value i for a spin component was obtained. From here weak value -1 for the weak value of the product was (correctly) inferred. However, autocorrelation of polarization cannot be deduced because the product rule does not hold for pre and post-selected particles, see [4].

In summary, direct demonstration of the failure of pigeonhole principle in the quantum domain has not been performed.

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Full control of dephasing dynamics — complex quantum networks

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Engineering, controlling, and simulating quantum dynamics is a strenuous task. However, these techniques are crucial to develop quantum technologies, preserve quantum properties, and engineer decoherence. Earlier results have demonstrated reservoir engineering, construction of a quantum simulator for Markovian open systems, and controlled transition from Markovian to non-Markovian regime. Dephasing is an ubiquitous mechanism to degrade the performance of quantum omputers. However, all-purpose quantum simulator for generic dephasing is still missing. Here, we demonstrate full experimental control of dephasing allowing us to implement arbitrary decoherence dynamics of a qubit [1]. As examples, we use a hoton to simulate the dynamics of a qubit coupled to an Ising chain in a transverse field and also demonstrate a simulation of nonpositive dynamical map. Our platform opens the possibility to simulate dephasing of any physical system and study fundamental questions on open quantum systems.

Following another line of research, we explore possibilities of using complex quantum networks of harmonic oscillators for reservoir engineering and quantum probing purposes [2,3] - including a possibility for their experimental realization with an optical multimode set-up [4].

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Resource-Prudent Communication via Quantum State Discrimination

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Hundreds of exabytes of data are sent through the Internet monthly and the demand grows exponentially. Meanwhile, the number of devices connected to the Internet will be well over three times the global population by 2022. With such an increase in data exchange rates comes massive growth in power and bandwidth usage, creating the need to optimize data exchange. Resource efficiency per communicated bit will have the paramount significance for proliferation of the Internet, energy efficiency of databanks and improved deep space communications. There are two main resources of a communication link: energy per bit and bandwidth. In most cases, there exists an unfortunate tradeoff in the use of these resources where a proportional improvement of one leads to an exponential increase of use of the other. One possible way to partially avoid this daunting tradeoff is the use of quantum measurement. Indeed, quantum state discrimination is limited by Helstrom bound, [1], that yields smaller error rates than shot noise limited classical state discrimination.

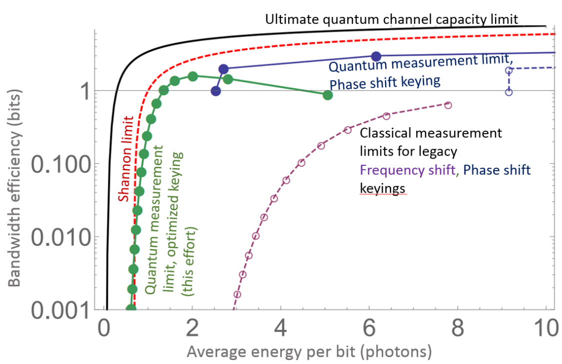

Figure 1: Bandwidth and power efficiency comparison of different communication protocols and the Shannon limit.

Two families of "M-ary" encodings are distinguished: bandwidth limited and power limited. The bandwidth limited family includes such encodings as pulse amplitude modulation (PAM), quadrature amplitude modulation (QAM), phase-shift keying (PSK) and others. In these modulation schemes the per-bit channel bandwidth W decreases as the number of signals in the alphabet M increases for a fixed bit rate R_b. Therefore bitrate and bandwidth ratio is $R_b/W > 1$. On the other hand, increasing M increases the error probability and thus reduces the performance at any given SNR, decreasing power efficiency. Remarkably, even though the quantum measurement yields some advantage over classical measurements for state discrimination, this advantage rapidly decreases with the growth of M for bandwidth-limited protocols, Fig. 1. The power limited family includes pulse position modulation (PPM), biorthogonal and simplex signal modulation and orthogonal frequency-shift keying (OFSK), uses orthogonal signals, and requires a broader bandwidth. For orthogonal signals bitrate to bandwidth ratio is $R_b/W < 1$. The two families, [2], reside in two separate semi-plains $R_b/W < 1$ and $R_b/W > 1$, i.e. energy efficiency and bandwidth efficiency are not optimized at the same time.

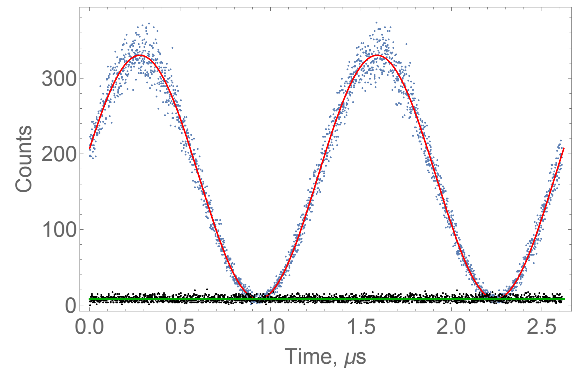

Figure 2: Histogram of time-resolved photocounts at SPD collected for 10 seconds for correctly and incorrectly hypothesized displacement to vacuum.

We found an encoding family whose Helstrom bound yields energy efficiency better than that of bandwidth-limited encodings and simultaneously yields bandwidth-efficiency better than that of power-limited encodings for $M > 4$, i.e its sensitivity bound resides in *both* semi-plains, Fig. 1. It is based on coherent frequency shift keying (CFSK) [3] with optimized parameters of the alphabet states. A quantum receiver is required to take advantage of this encoding. Such a receiver, [3], relies on adaptive displacement of the hypothesized most likely input state to vacuum, followed with time-resolved single-photon detection. Unlike other quantum receivers, this receiver uses timestamps for better sensitivity.

To demonstrate quantum-enabled communication we implemented the CFSK testbed experimentally. To characterize state displacement to vacuum, we measure time-resolved histogram of photon arrival timestamps, Fig. 2. Our input signal produced $\approx$0.05 counts per pulse on a Si single-photon avalanche photodiode. After displacement, we observed $5 \cdot 10^{-3}$ counts per pulse and no temporal dependence. When displacement is based on an incorrect hypotheses, we observe a periodic histogram with the frequency $\approx$ 762 kHz, the average count rate of ≈ 0.1 photon per pulse, and visibility of 0.954. The temporally resolved fringes show the beating between the frequencies and relative phases of the incorrectly hypothesized state and the input signal. In the above measurements, no correction for the background/dark counts of the detector and detector jitter were applied. In modeling the $M = 8$ receiver performance based on this characterization we find that energy sensitivity of our modulation scheme under the above experimental conditions can be favorable to that of bandwidth-limited $M = 8$ quantum receivers. Particularly, a receiver with overall $\approx 70\%$ detection efficiency is sufficient to achieve such a sensitivity.

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Continuous Variable Entanglement over Different Degree of Freedom for Multiple Bipartite State

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In this contribution we will show how the polarization d.o.f. of a pair of entangled modes is coupled to the optical orbital angular momentum giving, at the end, a pair of entangled modes that have orthogonal OAM and polarization. We also show how this experimental scheme can be extended to give more than a pair of entangled modes paving the way to CV entanglement multiplexing.

Quantum enhanced correlated interferometery

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Optical Interferometers represent one of the best sensing tool devoted to fundamental research. The recent detection of gravitational waves [8] being a prime example, where power recycled Michelson interferometers were used. Also, quantum metrology is a research field that deals with enhancing the resolution or sensing capabilities of a system by exploiting the properties of quantum states of light which is otherwise constrained by classical limits. Leading to this, a sub-shot-noise phase measurement in the Michelson interferometers by injecting squeezed state was suggested [5] and has already been realized in many gravitational wave detectors [6].

One of the current trends in modern physics for application of the optical interferometers is the search and study of omnipresent stochastic sources of noise such as exotic sources due to conjectured Planck scale effects [3] or gravitational wave background [7]. For this purpose, a double interferometer system namely Holometer, consisting of pair of 40m long power recycled Michelson interferometers placed close to each has been built at the Fermilab [4]. However, at this moment, the holometer is being operated using classical light only.

Following the proposal in [1][2], here we present the experimental results of exploiting the properties of quantum states of light in a coupled Power Recycled Michelson interferometers on a table-top setup. The scheme consists in injecting quantum states of light such as squeezed state and bipartite quantum correlated state into the interferometers and measuring the cross correlation between them. When two independent squeezed states were injected, we were able in detecting a faint test correlated phase signal with an amplitude several orders of magnitude below the shot noise limited sensitivity of a single interferometer. The joint sensitivity obtained for the double interferometric system with squeezed states injected was around 3x10-17m/√Hz around 13.5 MHz, in a few seconds of measurement time. The second phase of the experiment involved the injection of a bipartite quantum correlated state in the two interferometers. In this case, we have demonstrated a quantum advantage in detecting uncorrelated noise or difference in the two interferometers' signals enabled by the reduction of the noise in the output photo-current subtraction.

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Tunable, Narrow Band Correlated Photons Interfaced with Atomic Systems

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We report on the development of a new source for versatile correlated photon pairs, which are frequency tunable, atom-resonant, narrowband, single mode and entangled. The photons will be used to explore multi-photon processes with cold atoms, such as stimulated emission, stimulated Raman scattering and two-photon absorption. Outside of the artificial scenarios of cavity-QED, such processes are almost unexplored at the most fundamental, individual photon level. Thus, it is of both fundamental and practical interest to study these.

Our source can generate both degenerate and non-degenerate photon pairs at any pair of frequencies across a few-GHz bandwidth covering the ^{87}Rb D1 line. This frequency tuneability is important while addressing frequency shifted atomic transitions or in a Λ or V scheme when each photon of the pair is addressing a different transition. The photon pairs in combination with our single ^{87}Rb atom trap allow us to explore the dynamics of the nonlinear response of an atom to an input of photons [1], photon-photon interference effects mediated by an atom [2] and applications of this in quantum logic and quantum enhanced measurement.

We produce a single mode of time-frequency indistinguishable photons with a bandwidth equal to the unbroadened atomic transition linewidth, for efficient atom photon interaction. For this, we pump SPDC in a type II phase matched PPKTP crystal placed inside a bow-tie cavity of linewidth 7 MHz and Free Spectral Range (FSR) 500 MHz. Since SPDC is a broadband process, we reduce the number of modes coming out of the cavity by using the clustering effect. An additional KTP crystal helps increase the difference between the FSRs of the signal and idler photons through birefringence. This dramatically reduces the allowed photon frequencies to just 3 clusters separated by 70 GHz containing about 4 modes each.

We use three parameters to achieve tunability of the photon frequencies; A laser locked to the ^{87}Rb D1 line is used to stabilize the cavity, thereby ensuring the generated photons are atom resonant. This laser can be locked to different hyperfine transitions in the ^{87}Rb D1 line and would accordingly permit photons of only that frequency to exit the cavity. The same laser is also used to stabilize the pump frequency using an offset lock, which allows us to tune the pump frequency. Finally, we alter the birefringence of the KTP crystal through temperature tuning to change the FSRs of the signal and idler. Through this, we can control which signal and idler frequencies are simultaneously resonant in the cavity. The signal and idler are separately filtered using high finesse tunable filter cavities of 100 MHz linewidth, to ensure that only a single mode is selected. We present correlation measurements to show that the photons are genuinely single mode, narrow band, tunable and atom resonant, and interference measurements to show entanglement. DFG is used to characterize the spectral content of the unfiltered cavity output.

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Critical Components for Integrated Diamond Quantum Photonic Devices.

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The explosion of interest in exploiting fundamental quantum mechanical principles for new technologies is driving a significant worldwide effort to address problems difficult or impossible to solve with classical technologies. We aim to investigate the foundations of large scale integration of single photon sources, passive optical circuits (waveguides, splitters, cavities, resonators) and single photon detectors all on a monolithic single crystal diamond substrate. Such devices will be essential building blocks for scalable quantum information processing and communication.

iamond is well known to host over 500 optical centres, many of which display highly desirable quantum properties and indeed some essential foundations have already been developed independently with single photon sources and passive optical components already integrated into diamond photonic chips. But the translation to practical devices has been slow, and this is partly because for a practical, scalable platform for a monolithic quantum optics chip requires integration of three essential components. These are: (i) single photon sources, (ii) photonic routing (ie waveguides, cavities, splitters and (iii) single photon detectors.

In previous work, our group has demonstrated the fabrication, characterization and optimization of many single photon emitters in diamond. In the present work, we first report on a scalable method or the production of thin, free standing, strain free, ultrapure and ultrahigh quality single crystal diamond membranes of thickness less than 1 micron. These membranes are fully compatible with the fabrication of multiple, complex, optical structures on the same single crystal membrane. We report on the fabrication methods, processing, and surface functionalization and the range of potential applications of these membranes. [1]

Finally, we also report on progress towards the fabrication of integrated single photon detectors on iamond based on Boron doped superconducting nanowire detectors. By growing the nanowires epitaxially on the single crystal substrates, the detectors are expected to display superior properties in terms of increased bandwidth, higher quantum efficiency, and higher sensitivity to IR photons (1550nm in particular). When integrated with waveguides on the membranes, the prospects for a fully integrated platform for quantum optics appears to be most promising.

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On the phase precision parameter of nonclassical states

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It is well known that the nonclassical states play a crucial role in establishing quantum supremacy. This work is focused on the role of nonclassical states in the domain of optical quantum interferometry, where the precision achieved is greater than its classical counterpart [1]. Specifically, here we have computed phase precision parameter for a class of nonclassical states [2] and have investigated their applications in quantum interferometry in general and quantum metrology [3] in particular.

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Contextuality without access to a tomographically complete set

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The operational approach to contextuality due to Spekkens requires finding operationally equivalent preparation procedures. Previously these have been obtained by demanding indistinguishably under a set of measurements taken to be tomographically complete. That is, it is taken for granted that the experimenter has access to the full dimension of the system of interest. However, there may in fact be other measurements in the true tomographically complete set, which could break the operational equivalences and hence eliminate the putative contextuality. Here we design tests of contextuality that are immune to this effect for a given number of unknown measurements in the tomographically complete set, allowing contextuality to be demonstrated with weaker assumptions.

Decomposition of the completely symmetric state

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Entanglement problem is crucial for the development of quantum information theory. Due to the essential role of symmetry played in the field of quantum mechanics, in this paper, we consider a subclass of symmetric states in the bipartite system, namely, the completely symmetric (CS) states, which is invariant under any index permutation. With the special structure, these states possess some nice properties for the entanglement problem. And it is hoped to believe that the CS state is separable if and only if it is S-separable, i.e., each term in this decomposition is a symmetric pure product state. It was proved to be true when the rank is less than or equal to 4 or $N+1$.

After studying the properties of these states, we propose a numerical algorithm which is able to detect S-separability, within which, the sub-method admits the second order convergence rate. This algorithm is based on the best separable approximation, which furthermore turns out to be applicable to test the separability of quantum states in the bosonic system.

Besides, we analyze the convergence behavior of this algorithm. Some numerical examples are tested to show the effectiveness of the algorithm.

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REACHING FOR QUANTUMNESS THROUGH GENERALIZED SQUEEZED STATES

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Current definitions of both squeezing operator and squeezed vacuum state are critically examined on the grounds of consistency with the underlying su(1,1) algebraic structure. Accordingly, they are generalized so that all generators of the Schwinger two-photon realization of su(1,1) appear in the squeezing operator, and the vacuum state is the state annihilated by the lowering operator of the algebra, namely, a linear superposition of ordinary vacuum and single-photon state. The physical meaning of these generalizations is that additional degrees of freedom are available for the control of quantum optical systems. The resulting physical predictions are evaluated in terms of quadrature squeezing and photon statistics and particularly in the application to a Mach-Zehnder interferometer. The latter example shows the emergence of new nonclassical regions, characterized by negative values of Mandel's parameter, which cannot be anticipated by the current formulation, and then outline future possible use in quantum technologies.

Quantum entanglement near open timelike curves: theory and experimental simulation

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Closed Time-like Curves (CTCs) are one of the most striking predictions of general relativity. They may give rise to paradoxes (for example, the grandfather's paradox) that can anyway be solved in a quantum network model[1], where a qubit travelling back in time interacts with its past copy. However, the price to pay for the resolution of the causality paradoxes is the breaking of quantum theory's linearity. This leads to the possibility of quantum cloning, violation of the uncertainty principle and solving NP-complete problems in polynomial time. Interestingly, violations of linearity occur even in open time-like curves (OTCs), when the qubit does not interact with its past copy, but it is initially entangled with another, chronology-respecting, qubit. In this framework, the non-linearity is necessary to avoid violation of the monogamy of entanglement.

To preserve linearity and avoid all other drastic consequences, we discuss how the state of the qubit in the OTC can be described by a pseudo-density operator (PDO) - a recently proposed[2] generalization of density operators, unifying the description of temporal and spatial quantum correlations. Here we present a theoretical description of an OTC with the PDO and the results obtained with an OTC experimental simulation exploiting polarization-entangled photons[3], providing the first full quantum tomography of the PDO describing the OTC and verifying the violation of the monogamy of entanglement induced by the chronology-violating qubit. At the same time, we show that linearity is preserved, since the PDO already contains both the spatial degrees of freedom and the linear temporal quantum evolution.

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Decoherence control by feedforward decoupling

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Quantum sensors that are sensitive to external signals are intrinsically vulnerable to noise. State-of-the-art solution is to tailor the sensor's spectral sensitivity to enhance signals and suppress noise, usually implemented via complex dynamical decoupling sequences.

I will present an alternative approach that we termed "feed-forward decoupling". It is based on the insight that we can remove the decoherence effect of a classical noise source by recording it alongside the quantum signal and adapting the readout phase to the result. I will present a proof-of-concept implementation on a nitrogen-vacancy center disturbed by a randomly fluctuating current in a nearby conductor. The scheme effectively increases T2 in a Hahn-Echo measurement, and can moreover be extended to a self-learning algorithm that learns the noise-correction on the fly.

One of the most promising areas is instantaneous correction of strong control pulses, where small fluctuations translate into strong decoherence. I will specifically present our progress towards magnetic resonance imaging at the nanoscale, where we employ the novel scheme to apply strong magnetic field gradients for imaging.

QUANTUM VIOLATION OF THE PIGEONHOLE PRINCIPLE

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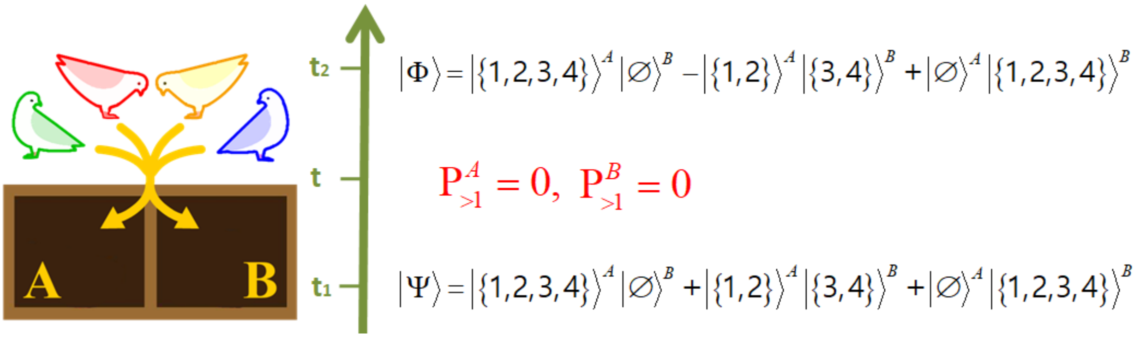
Pigeonhole principle states that if one put three pigeons in two pigeonholes, there must be at least one pigeonhole that contains more than one pigeon. This principle represents fundamental concept of counting, yet it can be violated in quantum systems!

In quantum world we define that a pigeon is in a hole if we can infer that the measurement of a presence of the pigeon in the hole will succeed with certainty. More than one pigeon in a hole X means that a measurement of the projection $\mathbf{P}^X_{>1}$ will succeed with certainty.

We found particular pre and postselected states $|\Psi\rangle$ and $|\Phi\rangle$ of four pigeons in just two holes, A and B, such that the result of measurement of such projection operator equals zero with certainty for both holes. (We can make the measurement in any of the holes, but only in one.)



Moreover, not only that there are no more than one pigeons in every hole, for these pre and postselected states there are no any pigeons in hole A and no pigeons in hole B! Every measurement in a particular hole will show that it do not have any pigeons at all! That is, a measurement testing that there are more than zero pigeons in each of the two holes will not succeed with certainty, namely $\mathbf{P}^A_{>0} = \mathbf{P}^B_{>0} = 0$.

This paradoxical situation can happen only when there is pre and postselection and requires sophisticated quantum measurements which tell us that there are pigeons in a hole without telling us how many pigeons are there. Note also that another sophisticated measurement which tests if there are exactly four pigeon in the hole A, will find them there with certainty. If instead we ask if there are exactly four pigeons in hole B the answer is yes too. So, in this particular pre and postselected state in every hole there are four pigeons and at the same time in every hole there are no pigeons!

We will also discuss a quantum pigeonhole paradoxes proposed by Aharonov and his collaborators [1, 2], which, although does not fulfill the failure of exact historical definition of the pigeonhole principle, allows feasible interesting implementation.

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Alberto Riccardi

Squeezing metrology (L. Maccone, A. Riccardi arXiv:1901.07482)

Quantum metrology has up to now focused on the resolution gains obtainable thanks to the entanglement among N probes. Typically, a quadratic gain in resolution is achievable, going from the 1/sqrt(N) of the central limit theorem to the 1/N of the Heisenberg bound. Here we focus instead on quantum squeezing and show that, similarly, one can attain a quadratic gain when comparing the resolution achievable by a squeezed probe to the best N-probe classical strategy achievable with the same energy.

Multipartite steering inequalities based on entropic uncertainty relations

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Quantum steering is a type of quantum correlation, owned by some entangled states of composite systems. It enables one subsystem to influence the state of the others, with which it shares the entangled state, by applying local measurements. The concept of quantum steering, for bipartite systems, was introduced in the early days of quantum mechanics by Schrodinger, who recognized that this class of states allow one part “to steer" the state of the other into an eigenstate of an arbitrary observable, and hence they express the \spooky action at distance" discussed in. Nowadays we are aware that three types of quantum entanglement exist: Bell nonlocality, steerability and nonseparability. Bell nonlocality correlations are the strongest ones and are owned by global states that violate some Bell inequalities, which are related to the non existence of local hidden variable (LHV) models. Then we have quantum steering, which was formalized in 2007 by Wiseman et.al as the incompatibility of quantum mechanics predictions with a local hidden state (LHS) model, where the parties have pre-determined states. At the bottom of the hierarchy there is entanglement , which can be defined as the existence of states of composite systems that cannot be given as a convex combination of states of the individual subsystems, namely separable states. All of these types of correlations have been generalized to multipartite systems, where there exist several different steering scenarios, depending on how many subsystems steer the others.

We investigate quantum steering for multipartite systems by using entropic uncertainty relations. We introduce state-independent entropic steering inequalities whose violation certifies the presence of different classes of multipartite steering . These inequalities witness both steerable states and genuine multipartite steerable states. Furthermore, we study their detection power for several classes of states of a three-qubit system.

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On the Conservation of Information in Quantum Physics

Marco Roncaglia

According to quantum mechanics, the informational content of isolated systems does not change in time. Considering composite systems, it would be very useful to identify suitable indicators able to quantify the informational content of the single parts and to describe their evolution through balance equations, as it happens in the case of energy.

Reasoning on the basic concepts of quantum mechanics, we show that there is an intrinsic quantum information encoded in the coherence of quantum states. Such information is measured by a function, called here coherent entropy, which turns out to be complementary to the von-Neumann entropy. We show that the total quantum information of multipartite systems is determined by the coherent entropy of the single subsystems plus their mutual information. Interestingly, the coherent entropy is found to be equal to the information conveyed in the future by quantum states, providing a further inspiring interpretation to this quantity. The vision proposed in this paper also suggests a natural and simple definition of an indicator for nonlocal correlations.

Continuous measurements for advanced quantum metrology

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We review some recent results regarding the use of time-continuous measurements for quantum-enhanced metrology. First, we present the underlying quantum estimation framework and elucidate the correct figures of merit to employ. We then report results from two previous works where the system of interest is an ensemble of two-level atoms (qubits) and the quantity to estimate is a magnetic field along a known direction (a frequency). In the first case [1], we show that, by continuously monitoring the collective spin observable transversal to the encoding Hamiltonian, we get Heisenberg scaling for the achievable precision (i.e. 1/N for N atoms); this is obtained for an uncorrelated initial state. In the second case [2], we consider independent noises acting separately on each qubit and we show that the continuous monitoring of all the environmental modes responsible for the noise allows us to restore the Heisenberg scaling of the precision, given an initially entangled GHZ state.

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High-precision multiparameter estimation of mechanical force by quantum optomechanics

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We have addressed a long-standing conceptual inconsistency in the estimation of a weak mechanical force probed by a mechanical oscillator. All current methods approximate small linearized forces by a displacement in position and momentum. However, a linearized force corresponds to a general Gaussian quantum mechanical process affecting the oscillator including both displacement and squeezing of position and momentum. Ignoring these squeezing effects makes the estimation incomplete and imprecise. Moreover, doing so, one can underestimate new mechanical effects and their applications. Taking squeezing into account turns the estimation immediately into a challenging multiparameter estimation problem. We have successfully solved this problem and demonstrated that the weak mechanical force could be indeed entirely characterized while keeping errors small.

On the other hand, the fast estimation of a linearized mechanical force requires the system being in the short-pulsed regime (stroboscopic). In this regime, the limited interaction of mechanical oscillators with light makes the optical readout of the oscillator inefficient. This restriction makes the multiparameter estimation procedure even more complicated. To solve this issue, we propose a scheme that keeps errors small despite the inefficiency of the optical readout and is also robust against the loss and noise involved in the mechanical process. For the first time, such a scheme can detect purely mechanical squeezing induced by the probed mechanical environment. We checked its feasibility for state-of-the-art experimental setups considering as well experiments currently under development.

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Experimental Fock-State Superradiance

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The full quantum mechanical treatment of spontaneous emission from an ensemble of atoms may lead to enhanced emissions in particular modes [1]. This phenomenon, known as superradiance, highlights the coherent nature of spontaneous emission. The complexity of the typical observations of superradiance, however, masks its quantum nature, allowing alternative classical interpretations. But the superradiant light emission in a Fock state is a genuinely quantum phenomenon, with no classical analogue.

In a set of theoretical and experimental works [2,3,4], we study superradiance with particular collective quantum states, and report its implementation in both the single- and two-excitation regimes. In our experiments, either one or two excitations are initially stored in an atomic memory. The memory readout process results in the superradiant emission of one or two photons, respectively, with properties that depend on the quantum state of the memory. Due to collective enhancement, the photon emission in the read process is highly directional, which permits an efficient detection by selecting the appropriate mode. Our main purpose is to observe the increase of the photon emission rate due to superradiance, together with the characterization of the Fock-state regimes with one or two photons being emitted by the memory. To do so, we measure the wave packets of the single-photon and of the biphoton emissions, evidencing superradiant acceleration in both cases, and we perform a photon statistics analysis that indicates the presence of quantum correlations. The experiments agree with a simple theory for the wave packets of the emitted photons.

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A model showing change of photon statistics of twin beam state from thermal to Poissonian and the advantage of photon subtraction in twin beam state for loss estimations.

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Absorption based measurement not only serves as base of spectroscopy and imaging, but it also finds application in all branches of science from chemistry and biology to physics and material science. However, the best sensitivity in loss estimation reached so far using classical probes is limited by shot noise. Albeit, it is known that the twin beam state (TWB) generated by spontaneous parametric down conversion (SPDC) process has thermal photon statistics in the individual modes, but its perfect photon number mode correlation allows surpassing the shot-noise limit reaching sub-shot noise sensitivity in the realistic scenario of loss estimation. In the recent years, symmetrical photon subtraction operation in the TWB has been shown to improve the individual mode photon statistics from thermal to sub-Poissonian. A question on fundamental ground naturally arises "does photon subtraction pave any advantage in noise suppression if the individual mode photon statistics of TWB becomes Poissonian instead of thermal".

In this work, we have devised a model (accounting detection losses), where changing the value of a parameter of the model changes the TWB individual mode photon statistics from thermal to Poissonian keeping the non-classical mode correlation intact. We then incorporated the symmetrical photon subtraction into the model and demonstrated advantage of it over TWB in the loss estimation with the change in the value of the model parameter accounting fixed per photon exposure to the absorbing sample. Furthermore, we have considered couple of different absorption estimators in this framework and compared their robustness in the loss estimation. We shall present results up to two photon subtraction and for all the values of the model parameter that changes the statistics of TWB from thermal to Poisonian and in between.

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Compressed sensing of twisted photons

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The ability to completely characterize the state of a quantum system is an essential element for the emerging quantum technologies. Here, we present a compressed-sensing inspired method to ascertain any rank-deficient qudit state, which we experimentally encode in photonic orbital angular momentum. We efficiently reconstruct these qudit states from a few scans with an intensified CCD camera. Since it requires only a few intensity measurements, our technique would provide an easy and accurate way to identify quantum sources, channels, and systems. We also propose an adaptive scheme that tremendously reduces the number of configurations needed to uniquely reconstruct any given quantum state without any additional a priori assumption whatsoever (such as rank information, purity, etc) about the state, apart from its dimension.

Single-photon spectroscopy of non-phase matched spontaneous parametric down conversion

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Spontaneous parametric down conversion (SPDC) is a useful tool for the generation of entangled photon pairs. In SPDC, biphotons are created by the direct decay of a pump photon into two daughter photons (signal and idler) inside a nonlinear material. Despite its great success, SPDC has only been achieved when the momentum of the pump photon is conserved by the signal and idler photons, which in turn limits the number of nonlinear materials suitable for SPDC generation. In this work we report for the first time the generation of entangled photon pairs in a 6 micron-thick layer of lithium niobate crystal via type-0 SPDC without satisfying momentum conservation. To corroborate the two-photon emission, coincidences between signal and idler photons were measured. Our results show a high coincidence to accidental ratio (CAR). In addition, we have characterized the frequency spectrum of the source by exploiting the spreading of biphoton wavepackets in a dispersive fibre [1]. The spectral width of SPDC for the crystal length used in this experiment is estimated to be 600 nm broad. However, due to the limited sensitivity bandwidth of the single-photon detectors the measured spectrum is only 200 nm broad, corresponding to a correlation time of 10 fs. The generation of entangled photon pairs without momentum conservation is not limited to lithium niobate, instead it opens the possibility to use higher nonlinear materials that can improve further the efficiency. Our source is adequate for applications that require the aforementioned properties, such as quantum imaging and distant-clock synchronization.

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Self-testing of maximally entangled state of arbitrary local dimension

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Introduction. Imagine that we are given a quantum device whose internal working is unknown to us and our task is to verify whether this device operates on the promised quantum state and performs the promised quantum operations on it, without opening this device, and thus destroying it. A possible way to tackle this problem is self-testing [1], which is a device-independent certification method, allowing to make statements about quantum devices only from the statistical data these devices generate. In recent years there has been a wave of results presenting self-testing protocols for various composite quantum systems and measurements. In particular, in [2], exploiting the results of [3], self-testing method for any pure entangled bipartite state was proposed. This method is, however, based on violation of many two-outcome Bell inequalities such as the CHSH [4] or the tilted CHSH [5] ones, and it remains a highly nontrivial problem to propose certification scheme of d-dimensional quantum states based on violation of a single d-outcome Bell inequality that uses genuinely d-outcome measurements.

Results. Here we address the above problem and propose a self-testing protocol for the maximally entangled state of any local dimension and the well-known CGLMP measurements [6]. Our result exploits a genuinely d-outcome Bell inequality proposed recently in [7] to be a generalization of the CHSH Bell inequality to scenarios involving any number of measurements and outcomes. To this aim, we exploit the sum of squares decomposition of this Bell inequality and show that up to local isometries the state and measurements maximally violating this Bell inequality is the maximally entangled state of two qudits and the CGLMP measurements.

Discussion. We propose the first, to the best of our knowledge self-testing statement for quantum system of arbitrary local dimension that does not rely on self-testing results for qubit states. Apart from being interesting from the fundamental point of view, we believe that our self-testing result can be used to establish unbounded randomness expansion from quantum correlations: the maximal quantum violation of the Bell inequality [7] certifies $\log_2 d$ of perfect randomness, while it requires one random bit to encode the measurement choice.

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Correlation Plenoptic Microscopy

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Traditional microscopy is affected by a strong trade-off between resolution and depth of field. Therefore, to image different planes of a sample, time-consuming scanning methods like confocal microscopy [1] must be used.

A recently developed technique, called Plenoptic imaging (PI), allows to refocus, in post-processing, an image acquired in a single exposure, with the result of enhancing dof and performing a 3D reconstruction [2, 3]. The idea behind it is the simultaneous acquisition of information on both spatial distribution and direction of light, performed by means of a microlens array inserted between the main lens and the sensor. However, the natural trade-off which is between resolution and depth of field is still present in plenoptic devices: collecting angular information by the use of microlenses limits the image resolution, that is now defined by the microlens size rather than by the diffraction limit, as set by the numerical aperture of the main lens. In addition, practical 3D imaging is strongly limited by the reduced change of perspective enabled by the small size of the microlenses.

To address these issues, we propose a novel plenoptic microscopy method, based on the concept of Correlation Plenoptic Imaging (CPI), namely a plenoptic imaging technique that exploits spatio-temporal correlations of chaotic sources to retrieve the image of the object of interest and the image of the focusing lens on two disjoint sensors [4]. By measuring correlations of intensity fluctuations between such disjoint sensors, CPI enables to obtain directional information while keeping spatial resolution at the diffraction limit [5–7]. The proposed Correlation Plenoptic Microscope exploits the intrinsic correlations of chaotic light from microscopic specimens to perform plenoptic 3D imaging at the full resolution determined by the objective lens, without requiring scanning techniques [8]. The schematic setup is reported in Fig 1.

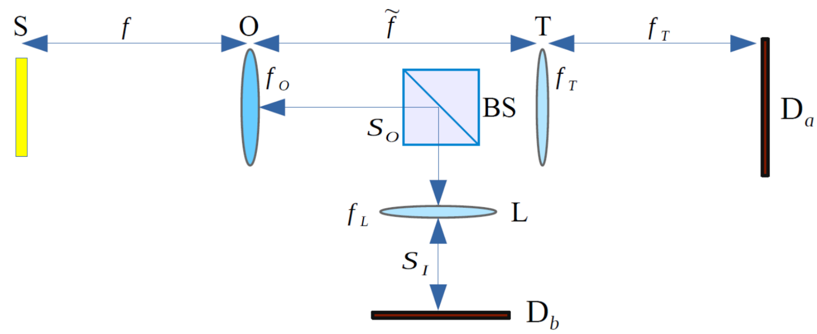
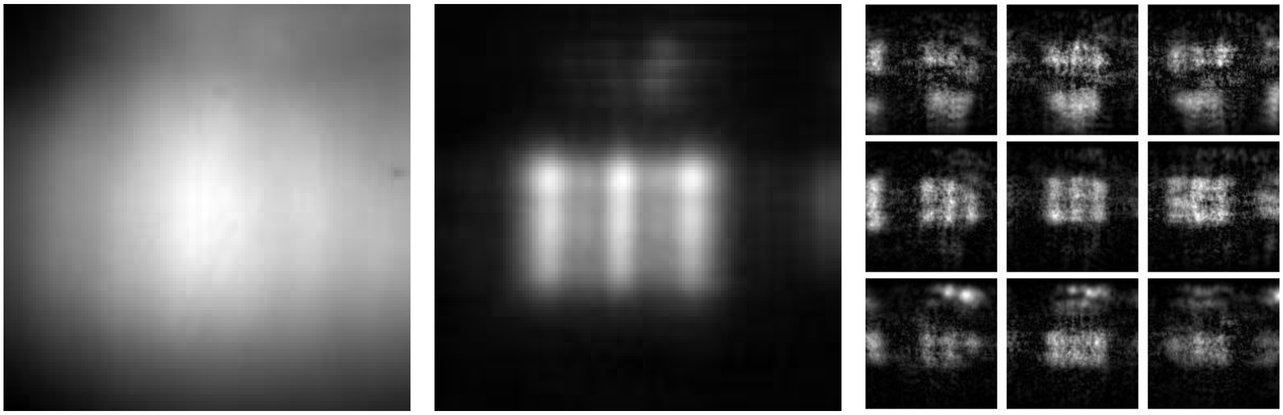


FIG. 1: Schematic representation of a Correlation Plenoptic Microscope, based on the correlated detection of the image of sample S on the detector D_a and the image of the objective lens O on the detector D_b. Light from the specimen S is divided in two optical paths by a beam splitter BS. In the transmitted path, the image of S is focused on D_a by the tube lens T, provided the distance f between S and O coincides with the objective focal length f_O. In the reflected path, an additional lens L focused the image of the objective lens O on D_b.

The correlation between intensity fluctuations at D_a and D_b ensures the correspondence between points of the two sensors and, therefore, between points of the sample and points of the objective lens, thus enabling plenoptic imaging and its peculiar ray path reconstruction. The parts of the specimen lying out of the objective depth of field, which appear degraded in the standard image retrieved by D_a can be refocused in post processing. Moreover, this technique provides much more points of view on the scene than a traditional PI device, allowing to perform an accurate 3D reconstruction.

The preliminary results of the experimental proof of principle are shown in Fig. 2. Here, the object is a triple slit with slit distance $d = 39\ \mu m$, placed at a 1.1 mm from the front focal plane of the objective lens O. In the left panel we report the out-of-focus image of the object, as retrieved by the ordinary microscope composed by the objective lens O and the tube lens T in Fig. 1. The central panel shows refocused image, in which the triple slit is fully visible. To get a feeling about the origin of this result, as well as the multiperspective capability of our scheme, in the right panel we show 9 different points of view on the out-of-focus triple slit.



(a) Standard image (b) Refocused image (c) Change of point of view

FIG. 2: Experimental result of Correlation Plenoptic Microscopy. The object is one of the triple slits of a 1951 USAF resolution test chart. From left to right: a) image of the object out of focus, b) refocused image, c) different points of view on the object.

On one hand, the proposed modality for correlation plenoptic microscopy overcomes the limitations of traditional PI, providing and unprecedented combination of resolution and depth of field. On the other hand, the technique covers a much wider range of applicability than the previously developed CPI setups, which were not effective in presence of scattering and/or randomly emitting samples.

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Convex optimization over classes of multiparticle entanglement

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A well-known strategy to characterize multiparticle entanglement utilizes the notion of stochastic local operations and classical communication (SLOCC), but characterizing the resulting entanglement classes is very difficult. Given a multiparticle quantum state, we first show that Gilbert's algorithm can be adapted to prove separability or membership in a certain entanglement class. We then present two reliable algorithms for convex optimization over SLOCC classes. The first algorithm uses a simple gradient approach, while the other one employs the accelerated projected-gradient method. For demonstration, the algorithms are applied to the likelihood-ratio test using experimental data on bound entanglement of a noisy four-photon Smolin state [Phys. Rev. Lett. 105, 130501 (2010)]. Our work not only sheds new light on the separability problem, but also provides a reliable tool for experimentalists to characterize the entanglement property of their quantum systems with confidence.

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Integrated multimode SU (1,1) interferometer

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Quantum enhanced metrology utilizes the advantages of quantum mechanics to achieve higher statistical precision in comparison with classical interferometry which is bounded by the standard quantum limit (SQL). The phase sensitivity of the conventional Mach-Zehnder interferometer (SU(2) symmetry) can be improved with using of non-classical states of light (NOON states, squeezed light) but the detection losses drastically destroy the squeezing and restrict the achievable quantum enhancement. In this sense the non-linear SU(1,1) interferometer, which is stable to the external losses and allows to improve the phase sensitivity beyond the SQL, seems to be a powerful tool.

The SU(1,1) interferometer can be constructed with using of two nonlinear elements exploiting either parametric-down-conversion (PDC) or four-wave-mixing (FWM). Beyond the improvement of the phase sensitivity the non-linear SU(1,1) interferometer enables the tailoring of the spectral profile and allows to generate a narrowband squeezed light [1,2].

For practical large-scale applications in quantum information processing free-space set-ups are not very reliable because of the experimental complexity that is required to achieve and maintain a precise and stable adjustment between the elements and due to the significant size of such systems. However, due to the small size and high stability integrated quantum optical systems are very promising in this direction [3].

In this work we combine outstanding properties of the non-linear interferometry and integrated platforms to explore the multimode SU(1,1) interferometer based on the LiNbO3 platform. Few-mode and strongly multimode regimes were studied with using of the Schmidt-mode approach. It was shown that the spectral properties of the squeezed light inside the SU(1,1) interferometer can be modified by utilizing different mode content. Behavior of the phase sensitivity with increasing the number of photons in the system was investigated. The supersensitive regions with the phase sensitivity beyond the SQL were found and analyzed.

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Separability of Completely Symmetric States in Multipartite System

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Symmetry plays an important role in the field of quantum mechanics. We consider a subclass of symmetric quantum states in the multipartite system N^{\otimes d}, namely, the completely symmetric states (CS states), which are invariant under any index permutation. It was conjectured by L. Qian and D. Chu [2] that the completely symmetric states are separable if and only if it is a convex combination of symmetric pure product states. We prove that this conjecture is true for the both bipartite and multipartite cases. Further we prove that the completely symmetric state is separable if its rank is at most 5 or N + 1. For the states of rank 6 or N + 2, they are separable if and only if it their range contain a product vector. We apply our results to a few widely useful states in quantum information, such as symmetric states, edge states, extreme states and nonnegative states. We also study the relation of CS states to Hankel and Toeplitz matrices.

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The physics of X-ray ghost microscope

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Unlike classic imaging devices in the visible spectrum, we do not have effective imaging lenses to produce the point-to-point imaging-forming function for high-energy, short-wavelength X-rays. Due to this, the X-ray imaging that we are accustomed to more closely resembles the projection of a "shadow" of the object rather than a true point-to-point image. Here, we present a technique that produces true point-to-point imaging of X-rays by adapting the mechanism of lensless ghost imaging of visible thermal light. This talk will analyze the physics of an X-ray microscope which is, in principle, able to produce X-ray images with 10-10 meter spatial resolution and 10-15 second temporal resolution. The key to understand the working mechanism of this X-ray microscope is the lensless point-to-point imaging-forming function measurable from the X-ray photon number fluctuation correlation or intensity fluctuation correlation.

Ghost imaging was first demonstrated in 1995 using entangled photon pairs through the measurement of coincidence counts between two separate detectors. Its point-to-point imaging-forming correlation is the result of two-photon interference: a pair of entangled photons interfering with the pair itself. 10 years later, we found that two-photon interference of randomly created and randomly paired photons in thermal state can produce a similar point-to-point imaging-forming correlation without the use of any imaging lens. This type of ghost imaging technique is commonly called lensless ghost imaging. The lensless point-to-point imaging-forming correlation is key for X-ray imaging devices because, as mentioned above, X-rays are unaffected by traditional lenses. The lensless ghost imaging is achieved through the measurement of photon number fluctuation correlation or intensity fluctuation correlation, which is the result of constructive-destructive two-photon interference. As an additional benefit of two-photon interference, this X-ray ghost microscope can be set up such that it is insensitive to optical turbulence (rapid variations in optical path length due to random changes in index of refraction).

Although the mechanism of the original ghost imaging experiments has been successfully explained as the result of two-photon interference, the concept of two-photon interference seems uneasy to accept from the view point of classical physics, especially for those who insist thermal light ghost imaging is the result of a "speckle-to-speckle correlation". Classified according to their experimental setup and working mechanism, we may find two classes of ghost imaging: (I) The observed ghost image is produced from two-photon interference. In idealized conditions, the two-photon constructive-destructive interferences result in a point-to-point image-forming correlation between the object plane and a unique image plane. This class of ghost imaging follows the two-photon interference mechanism of the 1995 ghost imaging demonstration of Pittman et al. (II) The observed ghost image is produced from a speckle-to-speckle correlation. For most cases of this type ghost imaging, the intensity speckles distributed on the object plane and on the ghost image plane are two identical copies of the speckles of the light source, which is very different from the point-to-point imaging-forming correlation produced from two-photon constructive-destructive interferences. The most vivid and direct pioneer demonstration of this was published by Bennink et al. in 2002. Bennink et al. used two back-to-back laser beams to produce a set of speckles on the object plane and the ghost image plane by means of a set of rotations of the two beams. Another similar scheme was later demonstrated by Gatti et al. in 2004. Gatti et al. produced two identical intensity speckles by imaging the speckles of a pseudo-thermal light source onto the object plane and the ghost image plane, respectively. A ghost image of the object was obtained from the coincidences between the two sets of identical speckles. We may consider the speckle-to-speckle correlation a classical simulation of the original point-to-point imaging-forming correlation. The working principle of class (II) ghost imaging is easy to understand and easy to follow; however, one should never expect to obtain high resolution and turbulence-free ghost image from two identical speckles of intensity distributions. The working principle of class (I) ghost imaging seems uneasy to understand and uneasy to follow. Indeed, the concept of nonlocal two-photon interference is beyond the scope of classical physics; however, that is the only mechanism to achieve the high resolution and turbulence-free point-to-point imaging- forming correlation.

Class (II) X-ray ghost imaging has been experimentally demonstrated recently. On the one hand, it is interesting to see ghost images from X-ray; on the other hand, their low resolution and quality seem to be useless compared to current X-ray imaging technology. People start to wonder: Is the expected high-resolution X-ray ghost microscope really possible? This talk will address this question and give a positive answer: yes, the expected high-resolution turbulence-free X-ray ghost microscope is possible, if done correctly.

Client-friendly Continuous-variable Blind and Verifiable Quantum Computing

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Quantum computers harness quantum mechanical properties to deliver computational speedups for classically-intractable problems. These promises have spurred technological advancements in quantum hardware, however, they remain elusive, and will likely be accessible only over a network. Compounding this with the needs of the consumer, protocols that protect quantum information during the evaluation are needed. To this end, we present a protocol for assisted quantum computing on continuous-variable (CV) platforms that is both *blind* and *verifiable* [1]. Blindness means that nothing beyond an upper bound on the number of non-Gaussian gates used in the evaluation is leaked to the server, and verifiable means that the client has a reliable certificate for the correctness of the computational output. This is achievable while only requiring the client to be able to perform Gaussian operations – a staple in most CV experiments.

The protocol proceeds as follows: The client breaks down her desired evaluation into a circuit diagram comprising of Gaussian gates, and a non-Gaussian gate, the cubic-phase gate. Any CV operation can be decomposed into these components. Let the number of cubic-phase gates needed be M, where the phase parameter of each gate, γ_k, for $k=1,\ldots,M$, can be any real number. The client requests $N+1$ copies of M cubic-phase states from the server, with a fixed encrypted phase $\tilde{\gamma}$. Upon receiving the states, the client retains one copy, ρ, and performs a verification test on the remaining N copies using the following fidelity witness:

$$W=\left(1+\frac{M}{2}\right)I_M-\sum_{k=0}^{M-1} I_k\otimes\omega_{k+1}\otimes I_{M-k-1},$$

where $\omega_{k+1}=\left(\frac{s^2}{2}\right)\left(\hat{x}_{k+1}^2+9\tilde{\gamma}^2\hat{x}_{k+1}^4\right)+\left(\frac{1}{2s^2}\right)\left(\hat{p}_{k+1}^2+2\tilde{\gamma}\,\hat{p}_{k+1}^3\right)+\left(\frac{1}{2s^2}\right)\tilde{\gamma}\left(\left(\hat{x}_{k+1}-\hat{p}_{k+1}\right)^3-\left(\hat{x}_{k+1}+\hat{p}_{k+1}\right)^3\right)$, $\hat{x}_k$ is the position quadrature of the k-th mode, and $\hat{p}_k$ is the momentum quadrature of the k-th mode. Notwithstanding the complicated form of ω_{k+1}, the key take-away here is that W is composed entirely of $O(M)$ terms accessible through Gaussian measurements alone. The measurement yields an estimate of $F=Tr(W\rho)$, then the client accepts the cubic-phase state from Bob if $F<F_T+\eta$, where F_T is a threshold fidelity and η is an estimation error that the client has to

decide *a priori* on. If the client accepts, she uses the remaining state ρ to carry out the requisite M cubic phase gates in her evaluation via CV gate teleportation. It is during this gate teleportation step that she would tweak $\tilde{\gamma}$ to the desired phase, γ_k, using a single-mode squeezing operation on the kth mode given by $S(\gamma_k/\tilde{\gamma})$. The output of this CV gate teleportation enacts the desired cubic-phase gate, up to the usual Gaussian correction factor.

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Quantum optics and information science in multi-dimensional photonics networks

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High-dimensional quantum systems based on single and multi-photon states offer an attractive platform for quantum information and technology applications. These include advanced quantum communication, quantum metrology as well as quantum simulations. Here we present three different approaches for the realization of multi-dimensional quantum states and networks, and discuss their potential for implementing tailored quantum systems.

Firstly, we present our latest progress for the implementation of integrated quantum devices based on titanium-indiffused, periodically poled lithium niobate (Ti:PPLN) structures. The use of waveguides structures, which harness a χ(2) –non-linearity, allows for the realization engineered devices with multiple functionalities. These include single- and multi-channel sources with extraordinary brightness, as well as complex circuitries with fast electro-optic control. Our latest chip implements a full Hong-Ou-Mandel experiment, including degenerate pair generation in orthogonal polarizations, linear elements, and fast active elements such as polarization rotators and an electro-optically controllable time delay.

Secondly, we demonstrate highly efficient devices based on non-linear waveguide structures for the preparation and manipulation of pulsed quantum light with an engineered temporal mode structure. Pulsed photon temporal modes are defined as field orthogonal superposition states, which span a high dimensional system. They occupy only a single spatial mode and thus they can be efficiently used in single-mode fibre communication networks. Using pulsed parametric down-conversion processes much effort has been devoted in recent years to engineer sources with uncorrelated spectra, which emit single temporal mode pulsed photon pairs with no intrinsic structure. Contrariwise, we can explore the multi-mode temporal states for multi-dimensional quantum information encoding. Here we show that we can obtain complete control over the three main ingredients for quantum applications, namely the efficient generation of different types of resource states with tailored entanglement properties, the targeted manipulation and processing of temporal modes, as well as their detection.

Thirdly, we report on our new quantum simulation results using time-multiplexed quantum walks as a versatile platform for implementing quantum networks with dynamic control. We have realized different graph structures and illustrate specific quantum propagation properties, which include measurement induced-quantum effects and quantum walk dynamics governed by a four-dimensional coin.

Can We Measure an Entanglement Measure?

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Entanglement is a resource and a main task in quantum information is to quantify the amount of such a resource. Within an axiomatic framework, various measures of entanglement have been suggested in the literature, from the entanglement of formation to geometric distances. While playing a conceptually crucial role, none of those can be explicitly calculated for a generic quantum state, with the only known exceptions of two qubits or pure bipartite states. Therefore, it is important in this context to introduce new functions providing lower bounds of entanglement measures that can be, both, calculated theoretically and measured experimentally (like, for instance the Rényi entropy). Here we introduce a new entanglement measure that for pure states is constructed by maximizing the variance or, equivalently, the correlation calculated over a complete class of Hermitian operators. For a bipartite pure state this measure can be written in terms of the quantum Fisher information. For general mixed states, the convex roof construction is lower bounded by the quantum Fisher information that provides a sufficient (but not necessary) condition for detecting a multipartite entangled. However, the quantum Fisher information can be itself framed within a resource theory after defining the appropriate class of free operations.

Certifying maximal amount of Genuine Randomness for any two-qubit entangled state

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Randomness has paramount importance in modern day information processing tasks such as secure cryptographic protocols, statistical simulations, and randomised algorithms. In this context, certification of Genuine Randomness (GR) is the crucial issue. It has been argued [1] that any theory satisfying the Predictability and No-Signaling (NS) conditions at the operational level leads to derive the testable condition that is known as Bell-CHSH inequality. As violation of Bell-CHSH inequality is necessary to certify GR (as NS is taken as a fundamental principle of nature), thus, it is relevant to study the quantitative relationship between the violation of Bell-CHSH inequality and the amount of certifiable GR.

It is possible to certify at most 2 bits amount of GR in 2 party- 2 measurements per party-2 outcomes per measurement (2-2-2) scenario. It has been shown [2] that in the 2-2-2 scenario, using a pure bipartite maximally entangled qubit state (singlet state) and with the small violation of the Bell-CHSH inequality, close to 2 bits of GR can indeed be achieved by a suitable choice of measurement settings. However, it is difficult to realise singlet state in practical scenario. Therefore, we propose an efficient protocol for an arbitrary bipartite entangled qubit-state where the amount of GR corresponding to Bell-CHSH violation can get enhanced up to 2 bits. On the other hand, we also established that entanglement and nonlocality are not commensurate with GR for any bipartite entangled qubit-state.

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Validation of multiphoton interference via machine learning

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Multiphoton interference is a fundamental physical phenomenon, that is believed to provide a significant resource for several quantum information processes, including quantum simulation of quantum metrology. A paradigmatic model based on genuine multiphoton interference is Boson Sampling, namely a computational model corresponding to sampling from the output distribution of n indistinguishable bosons evolving in a linear network. Indeed, it has been shown that such problem cannot be solved efficiently with classical resources, and it represents one of the most promising approaches to reach the regime of quantum advantage.

Given this intrinsic complexity behind multiphoton interference and its relevance as a quantum information resource, is becomes crucial to identify suitable methods to assess whether such feature is present in a given n-particle system. Within this context, the capability of Machine Learning to manipulate and handle large amount of data, as well as its ability to recognize hidden features in complex patterns, can represent a useful resource for this task.

We will discuss different Machine Learning techniques to assess the presence of multiphoton interference. We will first show how to employ pattern recognition techniques [2] to validate a given set of data against alternative models that attempt to reproduce the properties of multiparticle interference. Then, will show how to employ the t-distributed Stochastic Neighbor Embedding technique to map the output of Boson Sampling devices to two-dimensional images [3], and that such images present common properties that can be exploited for validation purposes. Finally, we will discuss how Machine Learning techniques can also be included as a tool in other, physically-based, statistical methods for Boson Sampling validation [4].

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Reconfigurable Laser-Written Integrated Photonic Circuits for Linear Optical Quantum Computing

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We present an architecture of fully reconfigurable universal multiport optical circuits on a glass chip. We demonstrate a 4-by-4 multiport thermooptically tunable interferometer fully fabricated using the femtosecond laser writing technology. Currently lithography is the technological standard for fabricating complicated reconfigurable photonic circuits. However, femtosecond laser writing provides the capability of very fast and cheap prototyping of both passive and active integrated photonic chips directly in the optical lab. Here we demonstrate that this technology is capable of producing complicated reconfigurable circuits for experiments in quantum optics and linear optical quantum computing. We use a universal multiport interferometer design to achieve full reconfigurability of the device.

The fabricated device performs at a switching time of 10 ms setting a record for tunable femtosecond laser written devices. We present a thorough analysis of reconfigurability using an adaptive tuning strategy and provide an accurate account of the imperfections of reconfigurable devices fabricated with the femtosecond laser writing technology and possible approaches to overcome the reported issues. The device was shown to produce arbitrary intensity distributions on the output with average fidelities exceeding 0.99. We believe that our work provides a new and valuable approach for fabrication of medium-sized active circuits, and will be of interest for the integrated photonics and quantum optical communities. This work was recently published in [1].

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Mixing of quantum states under Markovian dissipation and coherent control

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In the resource theory of non-uniformity, an initial quantum state can be transformed to any other that is majorized by it, by means of noisy operations, i.e. through access to maximally mixed ancillary states and unitary transformations that act jointly in the system-ancilla space. In this talk, we investigate the possible transitions between states (i.e., the induced preorder of states) when one restricts the unitary control to the quantum system alone and replaces the maximally mixed ancillas with a Markovian master equation, represented by a unital Lindbladian. As a main result, we present necessary and sufficient conditions for the Lindbladian dissipation to have the same converting power as that of noisy operations, namely, conditions for induced preorder to be again majorization. The results are towards understanding the resource-theoretic preorders of states when considering additional physically-motivated restrictions on the free operations of a resource theory.

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Quantum-optical Gate for Non-classical Squeezed Light

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The development of quantum physics has made not only a dramatic change in scientific thinking, but also opened up a new world of previously unseen opportunities and objects. One of the attractive quantum objects is non-classical light, which is in the center of scientific interest nowadays. Squeezed non-classical light gives the possibility to overcome the standard quantum limit of measurement accuracy, and also has applications in quantum information due to correlations between many photons in such light. Deep investigations of squeezed non-classical light are in close and inseparable connection with the development of quantum technologies and formation of new quantum-based world.

In order to fully utilize the possibilities provided by non-classical squeezed light, one must be able to control and manipulate its properties. This task is complicated due to the fact that squeezed light is a very fragile state. The use of common optical filters and devices would bring noise into the system, which will destroy correlations and light squeezing. Thus, the problem of managing the properties of squeezed light is a nontrivial issue, solution of which will push the development of quantum technologies.

In this paper, we propose such a method of managing the spectral and temporal properties that do not ruin the squeezed light and conserve its properties. It was shown that one of the most convenient ways to describe non-classical light is an approach based on the introduction of the so-called Schmidt mode basis [1]. Squeezed vacuum light can be represented as an incoherent superposition of individual Schmidt modes. In addition, each Schmidt mode carries all the properties of squeezed light. Therefore, it is very promising to work out methods of changing the signal in one or several separate Schmidt modes. We propose quantum optical gate, which is based on sum-frequency generation process and which is capable of solving stated issue.

Quantum-optical gate provides wide opportunities for managing the spectral signal of squeezed light, allowing to control the contributions (weights) of selected Schmidt modes, from the exchange of weights between two selected modes and up to complete blocking of the signal in a certain Schmidt mode. Quantum-optical gate can also be used to study and induce the phase differences between Schmidt modes of squeezed vacuum, what influences the spectral and temporal properties of outgoing signal. Also worth mentioning the possibility of converting the selected spectral mode of squeezed vacuum into a squeezed vacuum in well-defined Gaussian signal centered at the sum frequency.

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Nanofiber integrated single light emitters for efficient single photon sources

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Quantum information science addresses how uniquely quantum mechanical phenomena can enhance communication, information processing and precision measurement. Photons are appealing for their low noise, light-speed transmission and ease of manipulation using conventional optical components, and optical quantum circuits using linear optics have been demonstrated [1,2,3]. One of the crucial difficulties is the lack of efficient single photon sources. Current photon sources using spontaneous parametric down conversion inherently generate more than two photons in the output, and these excess photons cause significant error as the size of a quantum circuit increases. The second one is the efficiency of the gates.

Here we show our recent activities to tackle these problems using nano optical fibers with built-in microcavities. We realized ultra-thin tapered optical fibers (nano optical fiber) with a diameter as small as 300 nm, keeping the transmittance of the fiber more than 90% [4]. Using the nano optical fiber, we succeeded in coupling 7.4% of photons emitted from a single light emitter (CdSe/ZnS) put on the tapered fiber into a single mode fiber (SMF) [5], and coupling a tapered fiber with diamond nitrogen vacancy centers in diamond nanocrystals [6].

To improve the coupling of photons from single light emitters to SMF, solid-state microcavities combining ultra-small mode volume, wide-range resonance frequency tuning, as well as lossless coupling to a single mode fiber are integral tools. We have developed an integrated system providing all of these three indispensable roperties [7]. It consists of a nanofiber Bragg cavity (NFBC) with the mode volume of under 1 μm^3 and repeatable tuning capability over more than 20 nm at visible wavelengths. In order to demonstrate quantum light-matter interaction, we establish coupling of quantum dots to our tunable NFBC and achieve an emission enhancement by a factor of 2.7. We also performed detailed numerical analysis of photon emission from a single light emitter coupled with a nanofiber Bragg cavity [8].

We will also report our recent results on coupling novel single light emitters (defects in hBN) to nano optical fibers [9,10] and Manipulation of single nanodiamonds to ultrathin fiber-taper nanofibers and control of NV-spin states [11], and a novel non-contact detection of nanoscale structures using nanofibers [12].

Acknowedgement

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The quantum information supremacy of quantum interference based on correlation measurements in linear optics networks

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Multiphoton quantum interference underpins fundamental tests of quantum mechanics and quantum technologies, including applications in quantum computing, quantum sensing and quantum communication. Standard quantum information processing schemes rely on the challenging need of generating a large number of identical photons. In this talk, we show how the difference in the photonic spectral properties, instead of being a drawback to overcome in experimental realisations, can be exploited as a remarkable quantum resource. Interestingly, we demonstrate how harnessing the full multiphoton quantum information stored in the photonic spectra by frequency and time resolved correlation measurements in linear interferometers enables the characterisation of multiphoton networks and states, produces a wide variety of multipartite entanglement, and scales-up experimental demonstrations of boson sampling quantum computational supremacy. These results are therefore of profound interest for future applications of universal spectrally resolved linear optics across fundamental science and quantum technologies with photons with experimentally different spectral properties.

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Coherent optical frequency conversion for polarisation entangled qubits

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Realizing a global quantum network requires combining individual strengths of different quantum systems to perform universal tasks, notably using flying and stationary qubits [1, 2]. However, transferring coherently quantum information between different systems is challenging as they usually feature different properties, notably in terms of operation wavelength and wavepacket. To circumvent this problem for quantum photonic systems, we demonstrate a polarization-preserving quantum frequency conversion device in which telecommunication wavelength photons are converted to the near infrared [3], at which a variety of quantum memories operate [4]. Our quantum interface device is essentially free of noise which we demonstrate through near perfect single photon state transfer tomography and observation of high-fidelity entanglement after conversion. In addition, our guided-wave setup is robust, compact, and easily adaptable to other wavelengths. This approach therefore represents a realistic building block towards advantageously connecting quantum information systems based on the interaction of light and matter.

The physical implementation of our quantum interface is depicted in Fig. 1 [3]. A telecom photon at 1560 nm, out of an entangled pair, is wavelength-converted to 795 nm, where alkaline-atom based quantum memories operate, by means of coherent sum frequency generation (SFG, or up-conversion). More details are provided in the caption. With this setup, we have measured that the fidelity of the transferred entangled state, i.e. obtained after frequency conversion, is greater than 95%, showing the relevance of our approach thourgh this essentially noise-free operation.

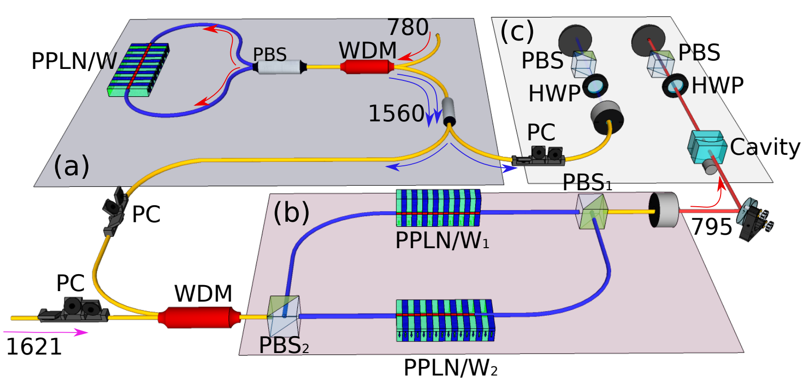

FIGURE 1. Experimental scheme. **(a)** Polarization entangled photon pair source based in a fiber-based nonlinear Sagnac loop. Photons pairs are created by SPDC into a type-0 PPLN/w at the degeneracy wavelengths 1560 nm. **(b)** Polarization-coherent up-conversion setup. Signal photons (1560 nm) and pump laser (1621 nm) are combined into a nonlinear fiber-based MZI. The horizontally (vertically) polarization components of the input are up-converted in the top (bottom) waveguide to a horizontally (vertically) photon, i.e. mode, at 795 nm. **(c)** Polarization analysis and Bell state measurements apparatus. The entangled pair, composed of the 1560 nm and 795 nm photons, are sent to two polarization state analyzers. The polarization rotation is implemented using two HWP optimized at their corresponding wavelengths and projected onto a beam splitter. The photons are fiber-coupled and detected by single photon counting modules permitting the registration of coincidence events. PPLN/w : periodically poled lithium niobate waveguide ; MZI : Mach-Zehnder interferometer ; HWP : half-wave plate ; WDM : wavelength division multiplexer ; PBS fiber polarization beam-splitter.

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Nonclassical features in off-resonant Raman process

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Raman process is used in a variety of applications, such as generation of nonclassical states, quantum repeater, quantum memory, quantum random number generator. A few of these applications use Raman process in off-resonance conditions. However, to the best of our knowledge, no serious effort has been made to study the nonclassical properties of the off-resonant Raman process. Here, we have reported that the detuning parameter (an experimentally accessible parameter) can be controlled to probe and enhance the nonclassicality generated in the output of the off-resonant Raman process.

Specifically, with the help of characteristic function obtained as function of detuning parameters in Stokes and anti-Stokes generation processes, the role of the resonance conditions in generation of nonclassical states is discussed. The joint photon-phonon number and integrated intensity distributions obtained in this case reveal a higher number of Stokes-phonon (pump-phonon) pair generation for the lower (higher) values of detuning parameter in Stokes generation. Pump-phonon pair generation is also supported by the lower values of detuning parameter in anti-Stokes generation. Further, significance of detuning parameters is also established with the help of a set of nonclassical features reported here which were not present in the Raman process at resonance.

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Organic molecules in integrated quantum devices

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Organic molecules of polyaromatic hydrocarbons were the first system in the solid state to show single photon emission [1,2]. However they are still considered unconventional sources of non-classical light. I will try to unveil part of the mystery behind such quantum emitters and show how they could effectively contribute to integrated quantum photonic platforms.

will report on fluorescence coupling from a single molecule to a planar optical antenna [3] and a single-mode dielectric waveguide [4] (Fig. 1, left), discuss the integration of single quantum emitters into hybrid dielectric-plasmonic devices [5] and the coupling with 2D materials [6]. I will present our recent results about the fabrication of single-molecule doped ancrystals, preserving the optical properties of the bulk system, i.e. negligible blinking and pectral diffusion [7] (Fig.1, right). Eventually, I will report on ultrafast time-resolved transient spectroscopy on a single molecule [8].

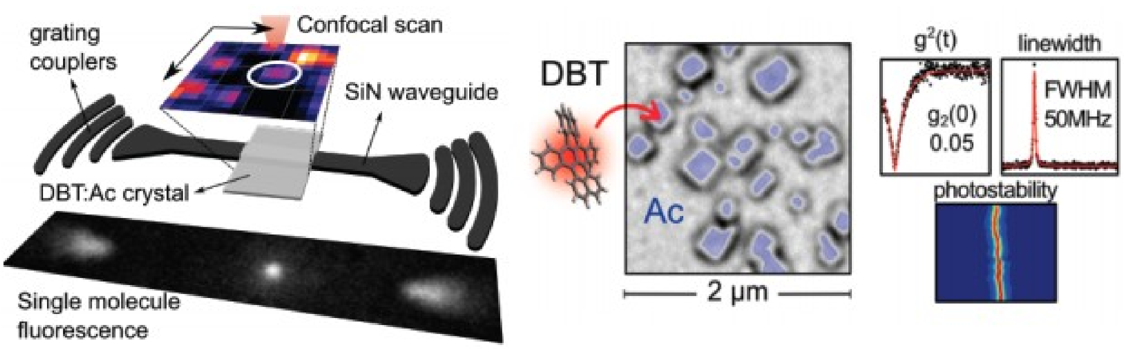

Figure 1: Left, concept for the device showing single molecule emission into an integrated photonic waveguide. Right, optical characterization of DBT-doped anthracene Nanocrystals.

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Thirring quantum cellular automaton

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The four-fermion interaction, describing the coupling between four fermionic fields at the same spacetime point, has been extensively studied in several Hamiltonian models, which differ each other in the symmetry of the interacting term. The Hubbard and the Thirring model are two notable examples of integrable systems with a four fermion interaction. Other relevant models are the Nambu-Jona-Lasinio and Gross-Neveu.

While the above systems have been studied both in the continuous space and on the lattice, they all share the continuous time of the unitary evolution.

Here we present a discrete time model of the four-fermion interaction and show its analytical solution in the two-particles sector. Analogously to any Hamiltonian integrable system, also in the discrete time case the solution is based on the Bethe Ansatz technique. However, the discreteness of the evolution prevents the application of the usual Ansatz, and a new Ansatz has been introduced successfully.

The analysis highlights non-trivial consequences of the discrete time in the physical phenomenology predicted by the model. The Thirring automaton exhibits scattering solutions with nontrivial momentum transfer, jumping between different regions of the Brillouin zone, in stark contrast with the momentum-exchange of the one dimensional Hamiltonian systems. A further difference compared to the Hamiltonian model is that there exist bound states for every value of the total momentum, and even for vanishing coupling constant.

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Towards standardization of single-photon sources measurements

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The current development of quantum technologies is already mature enough to establish standard techniques in single-photon metrology. Measurement of the $g^{(2)}(0)$ parameter plays a fundamental role in characterising and understanding single-photon emission. In this talk I will report on the pilot studies, performed by INRIM, NPL and PTB, on the measurement of the $g^{(2)}(0)$ parameter on test single-photon sources (SPSs) both in the visible and infrared spectral ranges. In the former case the SPS is based on a single Nitrogen Vacancy center in pulsed excitation, while in the latter case an heralded SPS realized by the process of parametric down-conversion is used.

Quantum Technology with Spin Centres in Semiconductors

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Luminescent defects in diamond and silicon carbide are among the prime candidates of physical systems for quantum sensing and quantum information. I will discuss recent progress in the characterization, manipulation and readout of such systems.

Magnetic field sensing based on nitrogen-vacancy (NV) centres is one of the most advanced forays of quantum science towards technological applications. A key obstacle to the performance of these systems is the cumbersome and inefficient readout method, based on photon collection. Recently, it was shown that coherent oscillations of the quantum state of NV centres can also be read out electrically by virtue of its spin-dependent ionization dynamics [1]. This method can achieve near-unity efficiency and speed up the spin readout by several orders of magnitude. I will describe the method, its limitations, potential improvements and the path towards the readout of single centres [2].

While the NV centre has spectacular spin properties, its optical transitions are far from ideal, motivating the need for an enhancement of the desired components of its photonic spectrum. Such an enhancement can be achieved with the use of microcavities. For several of the intended applications, such as scalable spin-photon entanglement for quantum computation and communication [3], it will be beneficial to create large numbers of efficient light-matter interfaces. I will discuss our progress in creating high-performance microcavity arrays using highly precise micromachining methods, which enable a mirror reflectivity rivalling that of the best available macroscopic substrates [4]. Lithographically defined alignment structures and tuning of the microcavities to the desired frequency using integrated micro-electromechanical actuators will also be described. Finally, I will discuss our efforts towards the integration of NV centres, and a promising candidate in silicon carbide [5] will be presented.

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Compensating side-channel effects in continuous-variable quantum key distribution

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The aim of continuous-variable quantum key distribution (CV QKD) [1] is in realization of highly efficient quantum cryptography using accessible components for optical communications. However, its practical realization substantially depends on imperfections of the realistic devices. It is therefore important to analyze the role of side channels, which are partially accessible to an eavesdropper, in security of CV QKD and suggest methods aimed at compensation of side channels in practical CV QKD. While some of the side channels, concerned with detector imperfections, can be ruled out using measurement-device-independent CV QKD [2], such schemes demonstrate higher sensitivity to channel loss compared to conventional CV QKD protocols. We therefore study how the side channels can be taken into account and possibly compensated for in the framework of standard device-dependent CV QKD protocols using coherent or squeezed states of light.

We consider side-channel loss on the preparation side of CV QKD protocols and side-channel noise infusion on the detection side of the scheme. We show how sender-side leakage after the modulation stage can be potentially compensated for by controllable addition of noise to the side-channel input. As for the leakage prior to detection, it constitutes a threat only to squeezed signals and can be compensated for by infusion of respectively squeezed states to the side-channel input. [3] Furthermore, we consider excessive modulation applied to auxiliary modes and directly leaking to an eavesdropper, which appears to be more threatening for squeezed-state protocols and may require optimization of squeezing. [4] On the detection side we show how monitoring on the residual noise from the side-channel noise infusion can be helpful for compensating the negative impact of the respective side channel [3]. Our results show the pathway towards highly efficient QKD secure against potential practical imperfections.

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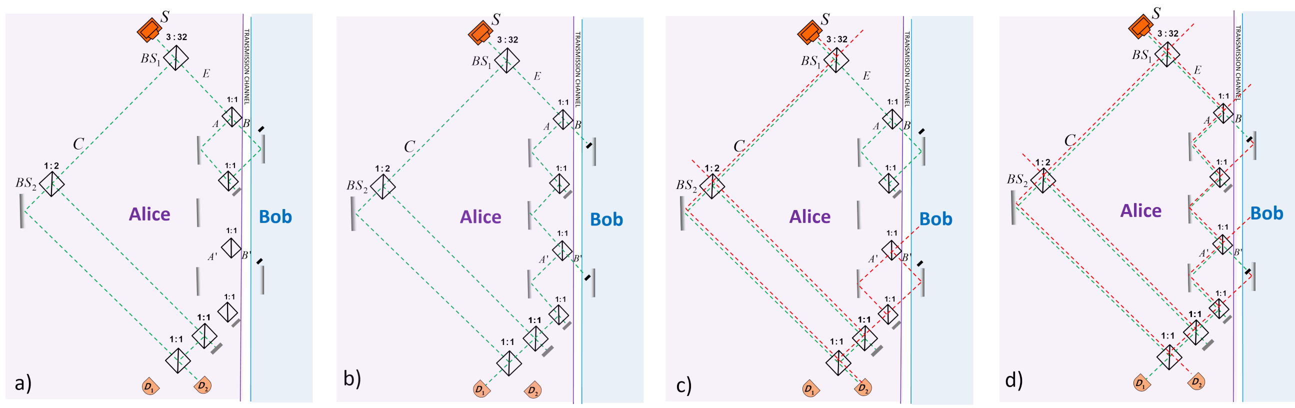
Quantum 2019, Torino, 27-31 May 2019

Communication without particles traveling between Alice and Bob

Lev Vaidman

The communication device is an interferometer, part of which is in Alice's site and part is in Bob's site. It is tuned such that depending on blocking or not blocking of the paths B and B' by Bob, Alice can get a click either in detector D_1 or D_2, see Fig. a,b. According to the protocol, Alice sends single photons into the interferometer from input port S until she gets a click in detector D_1 or D_2. Only events of such detections are considered. Accepting that the pre- and post-selected photons were present only in the overlap of the forward and backward evolving states, Fig. c,d, which corresponds to the places where the photon leaves a trace [1], it can be argued that no photon was leaving Alice's site and thus no photons were traveling between Alice and Bob.



In this protocol about 95% of photons are lost. There are other proposals claiming to perform communication without particles in the transmission channel [2], in which almost no photons are lost. However, in these proposals there is a nonvanishing probability of an error and, more importantly, the photons there do leave a trace in the transmission channel, so the photons travel between Alice and Bob [3,4]. However, introducing the combination of the two consecutive interferometers appearing in the right side of our scheme eliminates the trace in the transmission channel of these other protocols too, providing an efficient method for counterfactual communication [5].

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Coupling different degrees of freedom of light to study open quantum systems

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The interaction of a quantum system and its environment, i.e. open quantum systems can be described by a non-unitary operation associated with a quantum channel. One of the principal effects of an environment is the loss of coherence in the system, i.e, a loss of information codified in the system in favor of its surrounding. In this case, the system undergoes a Markovian dynamics. However, the flow of information does not need to be only one-directional: the information can be retrieved back to the system leading to Non-Markovian dynamics.

Different experimental approaches based on photonic entities have been devoted to show the implementation of controllable channels and the controlled behavior of open quantum systems dynamics. In this work, we report an all-optical experiment in which we implement a dephasing channel [1] and simulate different quantum dynamics [2] using the transverse spatial displacement of a beam that plays the role of the temporal variable. In our experiment, the polarization of light acts as the quantum system and the environment is represented by the transverse momentum of light. The coupling between these two degrees of freedom is done by means of a tunable beam displacer and the type of quantum dynamics is recognized by observing the behavior of the trace distance. The monotonic and non-monotonic behavior, of the trace distance, reveals Markovian and non-markovian dynamics, respectively. The observation of these two regimes is achieved by engineering the environment via spatial interference of light [3].

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Entanglement between living bacteria and quantized light

Vlatko Vedral

Oxford

A growing body of evidence suggests that biological processes could be utilising quantum coherence, superpositions, and even, in some cases, quantum entanglement to perform some tasks with higher efficiency. I will first briefly summarise the existing evidence, including two of the most famous examples of biological processes: photosynthesis and magneto-reception. I will then present the key features of modeling the flow of energy in complex systems. The main challenge is to obtain experimentally a handful of parameters believed to be important for describing the interplay between coherence (within the system) and noise (arising due to the interaction with the system's environment).

I will present single molecule spectroscopy experiments we are currently undertaking in our laboratory to obtain a better understanding of quantum effects in biomolecules, including living system. Finally, I will discuss how these experiments can be scaled-up, as well as how we can design artificial and hybrid biomimetic structures that mimic the underlying fundamental behavior. I will close by discussing an experiment with organic molecules (see Fig) conducted in my group and aimed at probing quantumness at the macroscopic level. This includes a recent observation of the vacuum Rabi splitting in a living bacterium strongly coupled with the electromagnetic field.

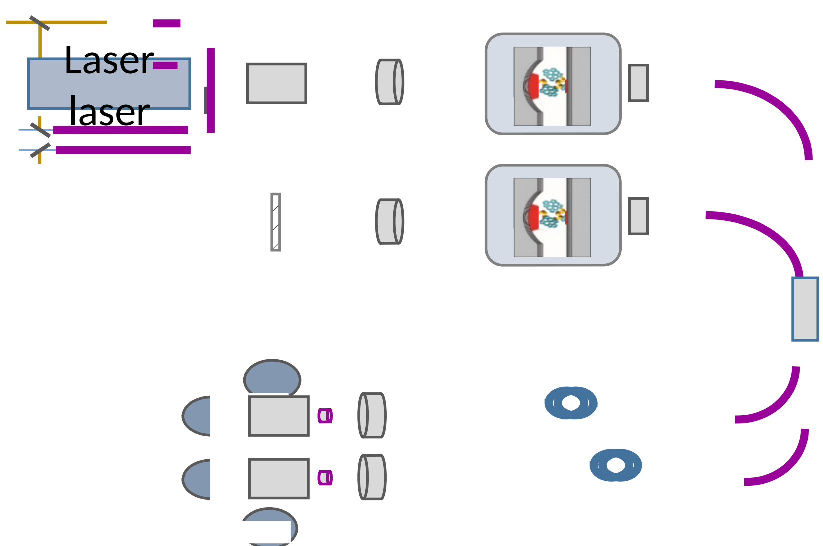

Fig. A typical experimental set up to entangled two physical systems (in this case organic molecules trapped in cavities). The laser provides light whose non-classical properties are then transferred to the molecules through light-matter interaction.

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Advances in Temporal Modes for Space Quantum Communications

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The selection of different degrees of freedom to be used for Space Quantum Communications allows to emphasise observables most suitable to address the interplay of Quantum Physics and Gravity on very long scale.

In the talk we shall describe some steps forward in the use of temporal modes for free-space Quantum Communications (QC). These were initially used to investigate the superposition principle on a Space channel [1,2] and are recently considered for an Optical Test of the Einstein Equivalence Principle [3]. A relevant development in the Lab use of the temporal modes includes the introduction of a scheme free from the post-selection loophole, when entangled stated, that may be extended to free-space channels [4].

Moreover, the experimental efforts to improve both the resolution in the temporal detection and the photon exchange scale has now reached the level of 250 ps along a real space channel [5] and the altitude of 20000 km [6] respectively.

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

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Genetic Quantum Measurement: a new measurement paradigm in Quantum Mechanics

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Measurements can be considered the very basic of Physics and in particular of Quantum Mechanics (QM), where they assume a crucial role. In the recent years, many novel quantum measurement paradigms have been introduced and tested, e.g. weak measurements, joint and sequential weak measurements, protective measurements. At INRiM quantum optics labs, we derived (and experimentally implemented) a novel measurement paradigm: Genetic Quantum Measurement (GQM), able to extract information on a quantum observable with improved accuracy with respect, e.g., to traditional projective measurements. In computer science, genetic algorithms, nowadays of widespread use for generating high-quality solutions to optimization and search problems, rely on bio-inspired operators mimicking the evolution mechanisms of mutation, crossover and selection. In QM the measurement procedure, following the von Neumann scheme, is described as a sequence composed of state preparation, interaction between quantum state and measurement device (described by a unitary operator), and state detection. GQMs represent a paradigm shift in this sense, since they use genetic-like approach to surpass the performances of the conventional (projector-based) quantum measurements. GQMs take advantage of a repeated sequence of interaction-recombination stages, leading to quantum interference (responsible for the crossover process), and selective measurements (corresponding to the genetic selection phase). The quantum mechanical superposition principle, at the heart of the quantum parallelism advantage, plays the role of mutation (needed to explore different evolution paths), allowing to explore all the possible "evolution trajectories" at the same time. In detail: GQMs, after the initial state preparation, are composed of a sequence of steps constituted by an interaction-interference part followed by a selective measurement (e.g. a repetition of the state preparation). The interaction-interference stage couples the observable of interest (OoI) with another observable (called Pointer) used to perform indirect measurement of the OoI. The initial quantum system -provided it survives the selection processes- is detected at the end of the whole sequence, where the Meter observable (canonically conjugated to the Pointer) is measured to extract (indirect)information on the OoI. The uncertainty associated to the OoI value results substantially reduced with respect to the one achievable with the usual quantum measurement approach when the number of individual quantum systems initially available, is considered. Note that, in most of the cases, the usual prepare-and-measure approach saturates the quantum Cramer-Rao Bound, representing the optimal quantum measurement providing the minimum uncertainty achievable. Thus, it could appear impossible for GQMs to be able to outperform such approach. But GQMs take advantage, during the whole measurement process, of the selective measurement, strictly connected with the preparation stage, accessing this way to additional information unavailable in the typical prepare-and-measure approach, as well as in the more general case of optimal quantum measurements. This essentially explains why GQMs should be able to provide outstanding performances in terms of uncertainty reduction. For these reasons, the GQM approach appears to be useful in all the possible fields where quantum measurements are involved, as quantum technologies and, in particular, quantum metrology, where it may represent a disruptive breakthrough.

Controllable formation of single-photon emitters in diamonds

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Diamond has a unique combination of physical properties that potentially meet the needs of next-generation optical and electronic devices. Strong attention is currently focused on methods of controllable generation of luminescent centers in diamonds, particularly nitrogen-vacancy (NV) and silicon-vacancy (SiV), which can be used as optical markers, electric and magnetic sensors, single-photon emitters. For this purpose, we are developing a new class of diamond materials, nanodiamonds produced from organic compounds at high pressure. In particular, we have synthesized nanodiamonds from its molecular analogue adamantane, controlling the size of crystallites in a wide range by changing the synthesis temperature. A minimum size of diamond crystals about 3 nm was reached [1]. The controllable NV and SiV formation in these nanodiamonds was demonstrated using the mixture of adamantane with other organic compounds containing nitrogen and silicon. For bulk diamond a new strategy of luminescent (NV) center production under diamond surface irradiation by femtosecond laser pulses was suggested, NV centers were effectively and controllably created in the nanoablation mode [2]. For submicron diamonds we have demonstrated their fundamental eigenmodes by scattering spectroscopy performed on single particles. It opens a simple way to improve the efficiency of diamond luminescence by choosing nanoparticles of a determined size [3].

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Super-and subradiance in free space

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We investigate directional super- and subradiance, observed with distant, non-interacting and initially uncorrelated sources incoherently emitting in free space [1-3]. In our approach, correlations among the sources are generated via successive measurement of photons at particular positions such that the detection is unable to identify the individual photon source. In this case, a system of initially fully excited two-level atoms cascades down the ladder of symmetric Dicke states each time a spontaneously emitted fluorescence photon is recorded [4,5]. Detecting m photons scattered from N > m atoms amounts to measuring the m-th order photon correlation function. Measuring this function thus allows (a) the production of any symmetric Dicke state from initially uncorrelated atoms and (b) the observation of superradiant emission patterns of the resultant Dicke states. As it turns out the same algorithm is also applicable for initially uncorrelated incoherently emitting classical sources [6]. In the latter case, the approach allows also the production of totally antisymmetric states with directional subradiant emission characteristics [7,8]. We apply these schemes to demonstrate directional super- and subradiance in different wavelengths regimes, i.e., in the optical as well as in the x-ray domain.

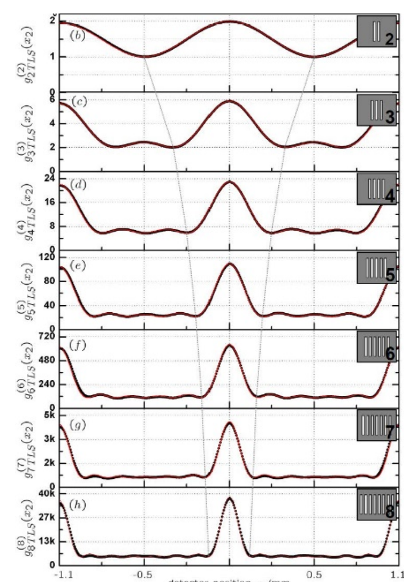

Fig. **1**: Measurement of the normalized m-th order correlation function for m = 2,…, 8 as a function of the position of the m-th detector for N = m statistically independent thermal light sources. The focussed emission of the m-th photon at $x_2 = 0$ after m-1 photons have been recorded at $x_1 = 0$ is clearly visible. The theoretical predictions are displayed by the red (solid) curves.

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Creation and interference of multiphoton states

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Quantum states of multiple photons are conjectured to enable all-optical quantum repeaters and quantum computers. While photon loss is ubiquitous and source and detection efficiencies are from perfect, there are models that can deal with these errors with reasonable overhead and the advantage that stochastic noise is very small in typical circuit implementations.

In our work on efficient semiconductor sources of multiphoton states we employ several types of quantum dots to create entangled photon pairs and photon triplets. Sophisticated growth and control techniques boost the efficiency and quality of the emitted quantum states. For example, with two-photon coherent excitation, we achieve high-quality time-bin entanglement [1] and nanowires act as antennas to guide multiple photons from a quantum dot molecule [2] to a collection lens.

Applying multiphoton states in any linear optical network involves multiparticle interference. Our theoretical results on the complete generalization of the Hong-Ou-Mandel interference covers all possible scenarios of an arbitrary number of bosons or fermions in an arbitrary multiport beamsplitter with a surprisingly simple criterion [3]. In a slightly different setting, we experimentally investigated the interference of a time-correlated three-photon state through Franson interferometry [4]. I will show how we achieved genuine three-photon interference with high visibility, which enables tests of the foundations of quantum mechanics.

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Communicating via ignorance & imaging via counting

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Abstract: Quantum technologies improve both communication and imaging. We transmit significant information through a completely noisy channel using indefinite causal order, an inherently quantum effect. We image remote bodies via photon-counting, achieving an order-of-magnitude more precision than traditional imaging methods.

Communicating via ignorance. Noise is everywhere, and naturally communication protocols aim to optimise the amount of information that can be sent through a channel with some given amount of noise. Intuitively, no information can be sent through a completely noisy channel. However, quantum physics defies this intuition, enabling information to be sent either via superposition of path, or superposition of causal order. Previous work has shown that: *path superposition*—placing two completely noisy channels in different arms of an interferometer—allows up to 0.16 bits to be communicated; *order superposition*—placing two completely noisy channels in a superposition so we are ignorant of channel order—allows up to 0.049 bits can be communicated. Here we improve on this, showing that perfect information transmission is possible, but only in the case of order superposition [1].

We use a quantum switch to achieve indefinite causal order, adapting the system of [2]: the order is controlled by the light polarisation and the quantum channels act on the transverse spatial mode of the light. We investigate two limiting cases. When both channels are fully-depolarising, the ideal limit is communication of 0.049 bits; experimentally we achieve 0.0341±0.0015 bits. When one channel is fully-depolarising, and the other is a known unitary, the ideal limit is communication of 1 bit, a capacity not possible with simple path superposition. We experimentally achieve 0.636±0.017 bits. Our results offer intriguing possibilities in applications ranging from communication through to imaging in turbulent media.

Imaging via counting. It is well known that there are physical limits to the precision with which an image can be formed. There are ways in which this limit can be circumvented, for example using super-resolution techniques that exploit the physical structure of the object, or object illumination with entangled states of light. However, in many applications—for example when the object is very far away—we cannot directly interact with the object, or illuminate it with entangled light: the quantum state of the light field is all that is accessible to the observer. Given a finite size imaging system in the far field—i.e., systems with a finite effective numerical aperture—we show the best way to extract the spatial characteristics of the light source.

We implement a general imaging method by measuring the complex degree of coherence using linear optics and photon number resolving detectors. In the absence of collective or entanglement-assisted measurements, our method is optimal over a large range of practically relevant values of the complex degree of coherence [3]. We measure the size and position of a small distant source of pseudo-thermal light, and show that our method outperforms the traditional imaging method by an order of magnitude in precision. Additionally, we show that a lack of photon-number resolution in the detectors has only a modest detrimental effect on measurement precision, further highlighting the practicality of this method as a way to gain significant imaging improvements in a wide range of imaging applications.

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Quantum control by measurement

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Measurements unavoidably leaves traces on a quantum system. While in the past this measurement back action was considered to be detrimental to any quantum application it eanwhile became clear, that well-timed measurements of controlled strength, indeed can steer the dynamics of a system in a well-controlled way. It even can impose dissipation on the system to reach quantum states which are not accessible by conventional coherent control. I will present a case where quantum measurements induce quantum random walks on a spin system akin bosonic sampling [1], where measurement of different strength induce a phase transition [2] or where it cools a mechanical cantilever [3,4].

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Towards High-Resolution Ghost Imaging with an Incoherent X-ray Source

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X-ray imaging is ubiquitous in medical diagnosis today, and in a completely different field, x-ray detection for the analysis of cosmic events is attracting increasing attention. In both cases, technological advances promise new capabilities for measurements based upon the Hanbury Brown and Twiss effect. Additionally, second-order correlation imaging with atoms and electrons have even been demonstrated recently.

In a previous paper [1], we described the first realization of x-ray "ghost" imaging with a simple table-top setup, without the need for a synchrotron beamline or monochromator; images of planar and natural objects with a much higher contrast-to-noise ratio compared to projection x-ray imaging were obtained for the same low radiation dose. We have now demonstrated ultra-low radiation computational ghost imaging with a true bucket detector; a resolution of 10 μm has been achieved for an x-ray tube source of size 37 μm, breaking the resolution limit of incoherent x-ray imaging. Moreover, the use of compressive sensing algorithms reduced the number of exposures required by an order of magnitude.

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Single-photon emission at 800 nm from colloidal quantum dots on sapphire surface at room temperature

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In this study, the single-photon-emission characterization of colloidal quantum dots at 800 nm wavelength at room temperature is investigated. The dynamics process, the blinking phenomenon and the antibunching effect for the photoluminescence from single quantum dots is studied. It is found that the optical properties of single quantum dots depend on the material surface, pump power and excitation time. The decay process of a single quantum dots can be fitted into a stretched exponential function. At low power excitation, a single photon source with a fluorescence lifetime of less than 0.5 ns is obtained from a single quantum dot on the surface of the sapphire. The value of the second-order correlation function at the zero point of the delay time is 0.02, which proves that the emission of a single quantum dot at 800 nm wavelength is high purity and high speed single photon source at room temperature. At long excitation time, the single photon count rate is gradually reduced, which is caused by photon bleaching of colloidal quantum dots. At high excitation power, the value of the second order correlation function at the zero point of the delay time increases due to multi-exciton emissions.

Quantum Field with Time as a Dynamical Variable and Spin-1/2 Particle

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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 of matter in space and time. The temporal vibration is a physical quantity introduced to restore the symmetry between time and space in a matter field. The wave function in quantum mechanics can be shown as a mathematical tool that describes the quantization of an underlying system with vibrations of matter in space and time. The emerged quantum field can have physical vibrations despite the overall phase of the wave function is unobservable. In addition, we investigate the properties of a self-adjoint operator for the temporal vibrations. The spectrum of this time operator spans the whole real line. It is not restricted by Pauli's theorem that time cannot be treated as an operator despite the Hamiltonian of the system is bounded from below. Based on the properties developed, we further our study for the intrinsic spin of a particle in the system. We find that the intrinsic angular momentum obtained can describe the properties of a spin-1/2 particle, and obeys the transformation rules of group SU(2).

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Quantifying the relative incompatibility of quantum observables

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Motivated by quantum resource theories, we introduce a preorder over orthonormal bases in a d-dimensional Hilbert space which intuitively corresponds to the degree of incompatibility between observables that are diagonal in those bases. The preorder is directly related to multivariate majorization and gives rise to families of monotones, i.e., scalar quantifiers that preserve the ordering. We relate the preorder with measures of quantum coherence, the strength of quantum fluctuations and entropic uncertainty relations.

Long distance and high speed Quantum Key Distribution

Hugo Zbinden

We will present the results of our latest QKD setup. Thanks to its efficient 3-state protocol, 1 decoy-state scheme and efficient and low noise superconducting single photon detectors, we manage to exchange over a distance of more than 400km. At shorter distances, we achieve > Mbits/s rate with realtime error correction and privacy amplification.

Nonlinear Quantum Optics in Nanoscale Waveguides

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We develop a systematic method for deriving a quantum optical multi-mode Hamiltonian for the interaction of photons and phonons in nanophotonic dielectric materials by applying perturbation theory to the electromagnetic Hamiltonian [1]. The Hamiltonian covers radiation pressure and electrostrictive interactions on equal footing. As a paradigmatic example, we apply our method to a cylindrical nanoscale waveguide, and derive a Hamiltonian description of Brillouin quantum optomechanics. We show analytically that in nanoscale waveguides radiation pressure dominates over electrostriction, in agreement with recent experiments [2,3]. We explore the possibility of achieving a significant nonlinear phase shift among photons propagating in nanoscale waveguides exploiting interactions among photons that are mediated by vibrational modes and induced through Stimulated Brillouin Scattering (SBS) [4]. We introduce a configuration that allows slowing down the photons by several orders of magnitude via SBS involving sound waves and two pump fields. We extract the conditions for maintaining vanishing amplitude gain or loss for slowly propagating photons while keeping the influence of thermal phonons to the minimum. The nonlinear phase among two counter-propagating photons can be used to realize a deterministic phase gate. Such photon-phonon interactions are exploited in order to generate a coherent mix of photons and phonons with manifest quantum phenomena [5].

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Marek Zukowski

General mapping of multi-qudit entanglement conditions to non-separability indicators for quantum optical fields

We show that any multi-qudit entanglement witness leads to a non-separability indicator for quantum optical fields, which involves intensity correlation measurements and is useful for field states of undefined photon numbers. With the approach we get, e.g., necessary and sufficient conditions for intensity or intensity-rates correlations to reveal polarization entanglement. We also derive separability conditions for experiments with mutually unbiased multiport interferometers. Within the standard detector inefficiency model these entanglement indicators work for any detection efficiencies. For specific cases, we show advantages of using local intensity rates rather than intensities. The approach with rates allows a mapping of Bell inequalities for qudits to ones for optical fields. Our results may find applications also in studies of non-classicality of correlations in "macroscopic" many-body quantum systems of undefined or uncontrollable number of constituents.

Quantum sensing to push the resolution limits in Magnetic Resonance Imaging

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Diffusion weighted imaging in Magnetic Resonance (MRI) is a powerful non-invasive technique for microstructure characterization. However, attaining microstructure resolution is still a challenge as the MRI resolution is much larger. Resorting to tools from quantum information theory, we analytically derive the ultimate precision limits for estimating microstructure sizes as the one given by restriction lengths in diffusion processes with diffusion weighted MRI sequences. We provide the control conditions, exemplifying with routinely gradient waveforms and with generic geometries of the microstructures, to achieve this precision limit in the estimation considering limitations imposed by T2 relaxation.