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Conference sections

A coherent states and squeezed states, phase space methods, quantum propagation [ICSSUR]

B continuous variables and quantum-information processing with continuous variables, generation of CV states [ICSSUR]
(This section is also supported by EU project COMPAS as a CVQIP workshop.)

C photon-number-resolving detectors, homodyne detection and other detection techniques, quantum measurement, quantum metrology [ICSSUR]

D photon pairs, their sources, properties and applications, entanglement and decoherence, generation of discrete quantum states, orbital angular momentum [ICSSUR,FF]

E atom and molecular optics, spins, cavity QED, Bose-Einstein condensates [ICSSUR]

F quantum computing, quantum memories, quantum cryptography, solid state quantum information processing [ICSSUR,FF]

G foundations of quantum theory [FF]

Quantum treatment of the time-dependent coupled oscillators under the action of a random force

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(oral, section A)

In this communication we introduce the problem of time-dependent frequency converter under the action of external random force. We have assumed that the coupling parameter and the phase pump are explicitly time dependent. Using the equations of motion in the Heisenberg picture the dynamical operators are obtained, however, under a certain integrability condition. When the system is initially prepared in the even coherent states the squeezing phenomenon is discussed. The correlation function is also considered and it has been shown that the nonclassical properties are apparent and sensitive to any variation in the integrability parameter. Furthermore, the wave function in Schrödinger picture is calculated and used it to derive the wave function in the coherent states. The accurate definition of the creation and annihilation operators are also introduced and employed to diagonalize the Hamiltonian system.

Quantum correlations and device-independent quantum information protocols

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(oral, section F, **invited** *)*

Given some correlations among several distant non-communicating parties, can they be obtained by performing local measurements on a quantum state? We introduce a convergent hierarchy of necessary conditions to characterize the set of quantum correlations. We also discuss the application of these concepts to the design of device-independent quantum information protocols.

Conditional preparation of optical non-classical states via coherent-state superpositions

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(poster)

Superposition of two coherent states are often referred to as Schrödinger cat states due to their resemblance of superposing macrosopic, distinguishable objects. Preparation of such superpositions for traveling wave optical fields is an experimentally demanding task, although there are a number of proposals and some experiments (see e.g. [1] and references therein). We propose a scheme based on Gerry's cross Kerr medium scheme [2] complemented by conditional homodyne measurement to produce even and odd cat states. Based on this scheme, more general superpositions of coherent states on a lattice and on a circle become available with a certain degree of freedom in the coefficients. Such superpositions, with already a small number of constituent states, approximate rather well certain non-classical field states [3]. For example, we demonstrate that photon-number state superpositions can be approximately prepared with the proposed scheme.

[1] S. Glancy and H. M. Vasconcelos, J. Opt. Soc. Am. B 25, 712 (2008).
[2] C. C. Gerry, Phys. Rev. A 59, 4095 (1999).
[3] J. Janszky, P. Domokos, S. Szabo, P. Adam, Phys. Rev. A 51, 4191 (1995); S. Szabo, P. Adam, J. Janszky, P. Domokos, Phys. Rev. A 53, 2698 (1996).

Mixed spin state entanglement and generalised Schwinger model

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(poster)

A new scheme for constructing a mixed spin density matrix has already been introduced to study spin squeezing [1] in some states of practical interest. Such a construction takes its inspiration from Schwinger's idea of realizing an $|sm\rangle$ as being made up of (s+m) 'up spinors' and (s-m) 'down spinors', all defined with respect to a single axis in space. The new scheme is employed here to study some of the well known entanglement measures which characterize the quantumness of a state. The suitability of employing such a generalized Schwinger model in characterization of classicality of states is discussed.Some well known states are considered for an in depth analysis.

[1] S. Sirsi, J. Opt. B 6, 437 (2004).

Geometric spin Hall effect of light

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(oral, section A)

Angular momentum (AM) of light is a topic that has recently attracted the attention of many researchers, from both classical and quantum optics communities. All the studies produced up to now considered the longitudinal component of the AM only, disregarding the components of the AM perpendicular to the propagation axis of

the beam. We recently started a systematic investigation of the properties of the transverse AM, and we found that it may be responsible for some intriguing and counter intuitive effects, as the ‘geometric spin Hall effect of light’ (geometric SHEL) presented here. SHEL is a phenomenon occurring when a light beam impinges upon an interface separating two different media. For example, when a linearly polarized beam of light is reflected or transmitted by a planar interface, it splits into its two left/right circularly polarized components. This split occurs in a direction perpendicular to the plane of incidence, as recently experimentally verified for a beam transmitted across an air-glass interface [1]. The occurrence of a similar left/right shift, affecting polarized light beams propagating along curved trajectories, has also been predicted and observed [2]. Geometric SHEL is a third type of left/right shift that occurs when a light beam is observed by a detector tilted with respect to the axis of the beam. The center of the beam, evaluated as the barycenter of the Poynting vector flux across the detector, shifts as the beam polarization changes from linear to circular. This shift is inherently connected with the existence of a transverse part of the angular momentum of the beam.

[1] Hosten and Kwiat, Science v319, 787 (2008).
[2] K. Y. Bliokh et al., Nature Photonics v2, 748 (2008).

Photon statistics in the macroscopic realm: methods to beat the lack of photon-counters

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(oral, section D, **invited** *)*

Measuring photon-number statistics might seem feasible only when photons are very few, owing to the notably poor photon-number discriminating capability of detectors, which hardly goes beyond five detected photons. Several efforts are aimed at improving photon-counting capability by working both on detectors and on front-end optics. Provided the light is spread across the sensitive area, detectors based on the most different primary photo-detection processes in which the output charge corresponding to one detected photon is generated in a confined area were (are being) shown to allow photon counting. Photons temporally spread by either cascaded arrays of beam splitters or multiple fiber-loop splitters have been alternatively used in connection with S-P avalanche diodes. It will be shown that any photodetector producing a S-P response sufficiently narrow can count photons up to numbers corresponding to the upper limit of the linearity range, which makes it feasible to measure statistical distributions in the macroscopic realm. This is exploited to obtain the reconstruction of the Wigner function of a field by using an unbalanced homodyning scheme. The method consists in counting the photons exiting a beam-splitter that mixes the field with a coherent probe field, whose amplitude and phase can be varied with continuity. Measuring a distribution corresponds to sampling the Wigner function in one point of the phase space. Our work may have perspectives in the applications of quantum optics that would gain from the use of intense fields and in those of statistical optics in which attenuating the fields for the sake of counting photons would either impair the statistics or make the measure time impractically long.

Quantum mechanics on phase space and star products: a group-theoretical approach

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(oral, section A)

The formulation of quantum mechanics on phase space and the related concept of star product of functions are remarkable achievements of theoretical physics. The prototypes of these notions are the formalism of Wigner distributions (which is strictly intertwined with the Weyl system) and the Groenewold-Moyal star product. Adopting a group-theoretical approach, we consider phase space realizations of quantum mechanics and star products of functions that are associated, in a natural way, with (in general, projective) representations of locally compact groups. The main properties of this general approach and the connection with the standard Weyl-Wigner-Groenewold-Moyal formalism are discussed.

Quantum time

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(oral, section G)

In relativity time and space are formally indistinguishable, the only obvious difference is that they enter the metric with opposite signs. But in quantum mechanics, time functions as a parameter. Like a butler, it escorts wave functions to and from experiments, but does not itself take part in the action. What happens if we release this restriction, if we let the butler join the party? To do this in a well-defined way, we distinguish between time in two senses. The first is laboratory time: what Alice measures with clocks. The second we refer to as quantum time, with properties defined by symmetry with respect to the properties of space. Now, consider the three dimensional wave function of a particle at a specific laboratory time. Extend this wave function in the time dimension. At each clock tick, the particle will now have an amplitude to be found a bit ahead or behind of its current time. Just as it does not have a well-defined position in space, it will not have a well-defined position in time. To generate the dynamics we use Feynman path integrals, which generalize in a relatively straight-forward way from three to four dimensions. If there are such quantum fluctuations in time, why haven't we seen them? In general, to see the effect of fuzziness in time in a scattering experiment, both apparatus and beam have to time dependencies of comparable scale, or any effects will be averaged out. If effects from quantum time normally average out, how to see? Experimental tests include: single and double slits in time, effects on a charged particle of time-varying electromagnetic fields, diffraction in time, ... Almost any foundational experiment on quantum mechanics may be turned into a test of quantum time by interchanging time and a space dimension.

Characterization of non-classical light sources for quantum information technologies

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(oral, section D, **invited** *)*

Non-classical light is the basic ingredient of quantum information technologies in the optical domain. With growing sophistication of experiments, detailed physical characteristics of non-classical light sources gains increasing practical importance. We review here our experiments revealing properties of fiber-coupled light generated in the process of spontaneous parametric parametric down-conversion. The first work determined the joint spectrum of photon pairs by Fourier transform spectroscopy. The difficulties resulting from the low brightness of the source were overcome by the construction of common-path interferometers that guaranteed stability of the setup over periods of hours. Spectral coherence of generated photons was characterized in a second work using an original scheme to measure the complete density matrix of a single photon. The off-diagonal elements of the density matrix were determined by detecting two-photon interference with a local oscillator prepared in a double-pulse shape. In the last experiment, effects of multiphoton events in parametric down-conversion were characterized with the help of photon number resolved detection. The experiments were carried out in parallel with the development of theoretical tools that enable efficient calculation of properties of down-conversion sources. The agreement between experimental results and numerical predictions confirms our good understanding of the physics of parametric down-conversion in realistic non-linear media.

Experimental proof of commutation rules by superpositions of quantum operators

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(oral, section A)

We directly prove the commutation relation between bosonic creation and annihilation operators by realizing an appropriate coherent superposition of sequences of single-photon additions and subtractions. The basic quantum operators were separately implemented in recent works and separate sequences of the two have recently allowed the direct experimental verification of the non-commutativity of the creation and annihilation operators. Here we present the experimental realization of a scheme for the arbitrary superposition of quantum operators and apply it to directly and completely prove the commutation relation. Besides its importance in the study of the foundations of quantum mechanics, the experimental access to arbitrary superpositions of quantum operators is of high interest for generating and manipulating quantum states for emerging technologies.

Extraction of a squeezed state in a field mode via repeated measurements on an auxiliary quantum particle

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(oral, section A)

The effect of repeated measurements on a system with continuum spectrum, consisting of a free particle, interacting with a second system with an infinite number of levels, consisting of a field mode, is investigated. The measurement protocol consists of repeatedly projecting the particle into a Gaussian state. The projected evolution operator that regulates the field mode dynamics between the consecutive measurements performed on the particle is then obtained. It is shown that, because of the measurement protocol, the spectrum of this operator is discrete and satisfying the criteria to obtain field mode extraction. In particular, the field is extracted into a squeezed state independently on its initial state. The dependence of the extraction speed with the number of measurements and the characteristic of the extracted state is investigated as function of parameters such as the interval between two measurements, the particle-field mode coupling constant and the Gaussian state width. Different regimes are observed and regions where one has quick extraction and strong squeezing are pointed out.

Combinatorics of creation-annihilation

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(oral, section G)

The Heisenberg-Weyl algebra, underlying virtually all physical representations of Quantum Theory, is considered from a combinatorial point of view. We provide a concrete model of the algebra in terms of graphs and discuss its relation to the classical lie algebras. Special emphasis shall be put on the efficient methods of discrete mathematics such as generating functions and graph decomposition. In this way, by drawing attention to the algebraic structure of Quantum Theory we intend to shed light on the combinatorial nature hidden behind its formalism.

Controlling the speed of light for applications in quantum information science

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(oral, section A, **invited** *)*

For the past decade or more, the optical physics community has been fascinated by the related phenomena of slow and fast light. These names are taken to refer to situations in which the group velocity (roughly, the velocity at which light pulses propagate through a material system) is very much different from the vacuum speed of light c. Several of the early stunning demonstrations of slow and fast light made use of atomic media. More recently, it has been realized that extreme values of the group velocity can also be realized in room-temperature solid-state materials, which are more suited for many practical applications. In this presentation, we will review some of

the physical mechanisms that can be used to induce slow-and fast-light effects in room temperature solids [1-3], and will describe the variety of propagation effects that can thereby be observed [4]. We will also present some ideas for applications of slow light within the field of quantum information science.

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[3] Y. Okawachi, M. S. Bigelow, J. E. Sharping,Z. Zhu, A. Schweinsberg, D. J. Gauthier, R. W. Boyd, and A. L. Gaeta, *Tunable all-optical delays via Brillouin slow light inan optical fiber*,Phys. Rev. Lett. 94, 153902 (2005).
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Emergence of quantum correlations from non-locality swapping

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(oral, section G)

By studying generalized non-signalling theories, the hope is to find out what makes quantum mechanics so special. Among the fundamental questions is the following: What physical principle limits quantum non-locality? This is still unknown today, but there is no doubt that answering this question will bring deeper understanding of the foundations of QM, as well as further developments in quantum information science. Up until now, there was one crucial aspect of QM that generalized models have failed to reproduce, namely its dynamics, in particular, the ability to perform joint measurements on two systems, which is the key ingredient for fascinating quantum processes such as teleportation and entanglement swapping. In fact, it was shown that there are no joint measurements in theories constrained only by the no-signalling principle, thus suggesting the existence of another fundamental principle inherent to QM, that generalized models fail to capture. Here we take a new conceptual perspective on generalized non-signalling models, which allows us to implement joint measurements. We revisit the paradigmatic model of non-signalling boxes (PR boxes) and introduce the concept of a genuine box. This allows us to present a model featuring rich dynamics, such as non-locality swapping, the analogue of quantum entanglement swapping, and teleportation. Joint measurements are implemented using an imaginary device called a coupler. Remarkably, part of the boundary between quantum and post-quantum correlations emerges in our study.

Quantum friction force on a moving atom

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(oral, section E)

Dispersion forces between polarisable objects are a well-known consequence of correlated ground-state quantum fluctuations of the interacting objects and the electromagnetic field. These forces, which include Casimir forces between bodies, Casimir-Polder forces between bodies and atoms and van der Waals forces between atoms, have been thoroughly studied in the past, inter alia on the basis of macroscopic quantum electrodynamics [1,2]. While investigations typically concentrate on the case of stationary objects, relative motion can lead to velocity-dependent dispersion forces, a phenomenon known as quantum friction. Studies of quantum friction often face the problem that a consistent and realistic quantisation of the electromagnetic field in the presence of moving bodies is not readily available. In this talk, we present a detailed investigation of the quantum friction on an atom moving with respect to a stationary body, where this problem does not occur. Starting from the Lorentz force and solving the coupled atom-field dynamics, we find a general solution for the quantum friction on atoms moving with nonrelativistic velocities. We apply our results to an atom near a plane surface, where it is found that the friction of an excited atom can be strongly modified when its transition frequency is close to the surface plasmon frequency.

[1] S. Y. Buhmann and D.-G. Welsch, Prog. Quantum Electron. 31, 51 (2007).
[2] S. Scheel and S. Y. Buhmann, Acta Phys. Slovaka 58, 675 (2008).

Hamiltonian formulation of quantum dynamics with separability constraints

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(oral, section G)

We analyze the Hamiltonian dynamical system that corresponds to the quantum system constrained on the manifold of separable states, using as an important example the system of two interacting qubits. The constraints introduce nonlinearities which render the dynamics nontrivial. We show that the qualitative properties of the constrained dynamics clearly manifest the symmetry of the qubits system. If the quantum Hamilton's operator has not enough symmetry, the constrained dynamics is nonintegrable, and displays the typical features of a Hamiltonian dynamical system with mixed phase space. Possible physical realization of the separability constraints is suggested.

Noise-assisted transport in biological quantum networks

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(oral, section F)

Transport phenomena in complex networks play an important role in many areas of physics, chemistry, and biology. Environmental noise does usually deteriorate the performance of these systems. Here we identify two key mechanisms through which dephasing noise, contrary to expectation, may actually aid transport of excitations through dissipative quantum networks by opening additional pathways. We investigate numerically and analytically noisy transport dynamics on a fully connected network and study numerically the Fenna-Matthew-Olson (FMO) complex, the former to elucidate the fundamental principles, and the latter to show how these principles can explain the remarkable efficiency (99 %) and robustness (against static disorder) of excitation energy transfer from the light-harvesting chlorosomes to the bacterial reaction center in biological photosynthetic complexes. These results strongly suggest the possiblity for achieving robust and efficient information/energy transfer, assisted by noise, by designing optimized artificial nano-structures for transport, for instance, in solar cells and in quantum information processing.

Open-system dynamics of graph-state entanglement

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(oral, section D)

Graph states constitute an extremely important class of entangled states with broad-reaching applications in quantum information, including measurement-based quantum computation, quantum error

correction, and secure quantum communication. Moreover, instances of this family play a crucial role in fundamental tests of quantum non-locality. Consequently, a great effort has been made both to theoretically understand their properties and to create and coherently manipulate them experimentally. Characterizing the dynamics of their entanglement under the unavoidable influence of the environment is however still a challenging task. In the present contribution we consider graph states of arbitrary number of particles undergoing decoherence and obtain lower and upper bounds for their entanglement in terms of that of considerably smaller subsystems. For an important class of noisy channels, namely the Pauli maps, these bounds provide the exact expression for the entanglement evolution. The present technique allows the calculation of entanglement for cases intractable so far, and leads to the direct identification, by inspection, of robust states against decoherence.

Narrowband filter for quantum light

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(oral, section E)

Atom-photon interaction promises to be a fundamental resource for applications like quantum computations. For an efficient interaction between light and atoms, the bandwidth of the light should match the natural linewidth of the atom transition to address. We present an atomic filter [1] that, together with cavity-enhanced down-conversion [2] source provides light spectrally optimized for interaction with rubidium atoms . The filter is based on the insertion of a hot vapor of rubidium into a balanced polarization interferometer. By optically pumping the rubidium with circularly polarized resonant light we induce a circular dichroism feature that changes the interferometer balance. This result in a peak in the transmission spectrum at the 'dark' output of the interferometer. The pump is tuned within the Doppler absorption profile of a transition such that the resonant velocity group is efficiently pumped, but other velocity groups experience little pumping effect, resulting in a sub-Doppler Lorentzian feature. The pump can be tuned to address different velocity classes of atoms, determining the central frequency of our filter within the Doppler width of the transition. The filter measured peak transmission is 15 %, it has a measured out-of-band extinction ratio > 33 dB and a measured background light noise low enough to make it compatible with low-photon rate sources. We will present the results of coupling a source described in [2] with the filter and how the resulting narrowband quantum light is used for measuring phase shifts in an optically pumped sample of rubidium vapors with a resolution equal to the Heisenberg limit in the ideal case.

[1] A. Cere et al., Opt. Lett., 34 1012 (2009).
[2] F. Wolfgramm et al., Opt. Express 16, 18145 (2008).

Continuous-variable quantum error correction: possibilities and impossibilities

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(oral, section F)

I will first discuss the impossibility of Gaussian quantum error correction, and will prove a related no-go theorem. I will show that a Gaussian channel parameter, denoted 'entanglement degradation', can only increase within a Gaussian encoding/decoding error-correcting scheme. Then, a realistic Gaussian erasure-correcting code will be introduced, which can protect the transmission of continuous-variable states of light in a probabilistic lossy channel that is intrinsically non-Gaussian. This continuous-variable erasure-correcting code will also be converted into a continuous-variable erasure filtration scheme. The experimental feasibility of this latter scheme will finally be discussed.

Unraveling the convex set of non-Gaussian mixed quantum states that are characterized by a classical probability distribution in phase space

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(oral, section B, **invited** *)*

According to Hudson's theorem, any pure quantum state with a positive Wigner function is necessarily a Gaussian state. Pure Gaussian states can therefore be viewed as 'classical' since they can be characterized by a genuine probability distribution in phase space. I will present a step towards the extension of this result to mixed quantum states by finding upper and lower bounds on the degree of non-Gaussianity of states with positive Wigner functions. The bounds relate the degree of non-Gaussianity of a state, its purity, and the purity of the Gaussian state having the same covariance matrix. Although these bounds are not tight, they permit us to visualize the convex set of non-Gaussian mixed states with positive Wigner functions. As a side result, I will also exhibit a bound on the lowest purity of states with a positive Wigner function and given covariance matrix, which implies that, rather counter-intuitively, Gaussian states are not necessarily the 'most random' states. (Joint work with A. Mandilara and E. Karpov)

Experimental realization of linear-optical two-photon gates

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(poster)

Quantum-information processing requires precise control and manipulation of the states of quantum systems. In particular, two-qubit entangling unitary gates lie at the heart of many protocols and they are,

together with single-qubit operations, sufficient for universal quantum computing. A universal quantum computer can be built with these resources despite the fact that the basic gates are only probabilistic and have some finite probability of failure.Quantum filters represent an additional resource for quantum information processing. These probabilistic non-unitary operations are required for diverse purposes ranging from discrimination, cloning and estimation of quantum states to entanglement concentration and distillation and quantum error filtration.Our experimental setup realize device for class of two-qubit gates for polarization states of photons. It operation is based on combination of single- and two-photon interference, selective attenuation, and conditional detection. Different gate operations, including the SWAP and entangling SWAP, can be obtained by changing a classical control parameter, namely, the path difference in the interferometer. Moreover, tunable two-qubit state filtering enables an arbitrary attenuation of either symmetric or anti-symmetric part of the input two-qubit state. The device is very versatile and the degree of symmetrization or anti-symmetrization can be easily set adjusting the transmittances of variable attenuators. A full quantum process tomography of implemented operations was carried out and the results confirm very good performance of the two-photon gates.

Wigner distributions for finite even dimensional systems without doubling

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(oral, section A)

The Wigner distribution, as originally defined by Wigner for the case of a Cartesian configuration space has, over the years, been extended and generalised in many directions. These include situations where the coordinates take values in (i) a finite field F_{p^n} (ii) a ring Z_N (iii) a finite group (abelian or non abelian) (iv) the manifold of a semi simple Lie group The first two are of particular interest owing to potential applications to quantum information processing and quantum state estimation. In the present work we focus our attention on the second case and set up the phase space and Wigner distributions thereon using what we call a Dirac inspired approach to Wigner distributions developed by us . This approach essentially requires computing the square root of a certain kernel which brings with it undetermined signs, one at each phase point. We examine the question as to what extent these signs can be fixed or related to each other by the marginals property i.e by demanding that the phase space averages of the Wigner distribution along an 'isotropic line' yield a probability. For the case when N is odd one finds one can consistently impose marginals property on all 'isotropic lines' which in turn uniquely fixes all the signs. The Wigner distribution thus obtained turns out to be the same as that already known in the literature. For the even case, on the other hand, this is not so and we show that the amount of freedom in choosing the signs is entirely governed by the the powers of 2 present in N and therefore it is sufficient to consider the case $N = 2^n$. Restricting ourselves to such dimensions, we find that the marginals property can not be consistently imposed on all the 'isotropic lines' but only on specific subsets thereof (i.e. on indvidual orbits under $SL(2, Z_N)$). Therefore the best one can do is to is to demand the marginals property on the largest such subset. This is actually good enough as the 'isotropic lines' in this subset (and only in this subset) cover all phase points. We explicitly carry out this out and find that, unlike the odd case, not all signs get fixed and therefore one has a family of Wigner distributions characterised by $3.2^{n-1} - 2$.different choices for the signs , all of which respect the restricted marginals property. We also examine the the eigenvalue spectra of the phase point operators and find that the number of spectrally distinct choices is rather small. Thus for $N = 2, 4, 8, 16$ those which have distinct spectra are only 1,3,4,15 in number respectively. We emphasise that here we work all along with an $N \times N$ phase space. This is in contrast to other formalisms to be found in the literature where a $2N \times 2N$ phase space is invoked to arrive at a satisfactory definition of Wigner distributions for an N-state quantum system)

Four-partite CV entangled states in aperiodical nonlinear photonic crystal

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(oral, section D)

Entanglement is one of the most valuable features of quantum mechanics. It plays a central role in quantum information and quantum computation. The entanglement of continuous quantum variables represents practical interest alongside with that of discrete variables [1]. One of the valuable property of quantum entanglement of CV states is related to high brightness of their optical fields. We consider a new scheme of forming bright four-partite CV entangled states in nonlinear photonic crystal. Aperiodical structure of such a crystal enables to implement simultaneously several nonlinear optic interactions [2, 3]. We study nonlinear optical interaction involving four parametric down-conversion processes at high frequency pumping. Four modes are generated in the interaction, so that photons of each mode are created by two down-conversion processes. We examine the behavior the photon number correlation from second to fourth orders, correlation matrix for continuous variables and their (bipartite) entanglement. We also study the entanglement of the process as a whole using separability criterion based on partial scaling transformation. It is also established that under specified nonlinear coupling coefficients a four-mode cluster states are formed.

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Conditions to preserve quantum entanglement of quadrature fluctuation fields in electromagnetically induced transparency media

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(oral, section A)

We study the propagation of quantum fields through an electromagnetically induced transparency (EIT) medium with two squeezed and one coherent states initially. Conditions to preserve and to establish non-separation criteria for perturbed quantized fluctuation fields are demonstrated. The results in this work provide a guideline for using EIT media as quantum devices of light.

The photon and the vacuum cleaner

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(oral, section D, **invited** *)*

Photonic quantum technologies are largely based on the effects of quantum interference coupled with the nonlinearities that can be induced by measurements. This means that attention must be paid to the character of the individual light particles that are used to build up large-scale entanglement. In turn, this requires the development of sources and detectors that can verify the quantum state of the light field in all its degrees of freedom. I shall discuss how 'vacuum engineering' can be used to prepare pure-state single photon wavepacketsusing nonlinear optics and conditional detection. The efficiecy of such methods of preparation is predicated on the ability to

understand what it is that the detector is measuring, and I shall illustrate a procedure for fully characterizing a quantum detector using tomography, thereby verifying the measurement operations for the device.

Atomic multiport beam splitters and their applications

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(poster)

Optical beam splitters are of great importance in quantum optics and information processing. Recent work using cold atom beam splitters shows the possibility of wider applications for these devices. By theoretical investigation we have shown how atomic multiport beam splitters can be made and used to make precision measurements of phases such as rotations. Our system consists of an optical lattice ring of various numbers of sites with cold atoms trapped at their potential minima. This has been studied at a microscopic level using a second quantised formalism in order to fully understand the quantum nature of the system.

Transfer of angular spectrum and quantum image formation with four-photons generated by a PPKTP crystal

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(poster)

In this paper, we study the four-photon state generation in the process of spontaneous parametric down-conversion with a periodically

poled crystal and show that it carries information about the angular spectrum of the pump beam incident to the crystal. This angular pump spectrum transfer allows one to control the transverse correlation properties of the four photon state by manipulating the pump field, with consequences for a broad class of experiments. The effect is demonstrated theoretically and experimentally, in connection with the formation of fourth-order images with the four-photons down-converted beams. These results generalize previous two-photon studies for four photons [1].

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Role of squeezing in BEC interferometry

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(poster)

A two-mode theory of interferometry [1] with Bose-Einstein condensates will be presented, highlighting the role of phase squeezing and entanglement in optimising features of the quantum correlation functions used to interpret interferometry effects in experiments where either a single component condensate is trapped in a double well, or a two-component condensate in a single well interacts with microwave fields. Decoherence effects due to the presence of non-condensate modes are also treated, using a phase space method [2] involving stochastic equations for condensate and non-condensate fields.

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Transport by quantum interference in systems of ultracold atoms

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Quantum Interference is not usually associated with transport phenomena. We study a few distinct mechanisms of how coherence and quantum interference effects can be utilized to generate transport of atoms over finite spatial distances. They rely upon time varying parameters to induce changes in the interference patterns to generate net unidirectional, but reversible flow. A class of such mechanisms creates flow in an open system, and is known as quantum pumping, previously considered theoretically in electronic mesoscopic systems, but without firm experimental confirmation. Another involves transport among a set of finite wells in a closed system with analogies with Stimulated Raman Adiabatic Passage (STIRAP). We demonstrate experimental feasibility of these mechanisms with available systems of ultracold atoms in microtraps.

Entanglement in a Raman-driven cascaded system

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(poster)

The dynamics of a cascaded system that consists of two atom-cavity subsystems is studied by using the quantum trajectory method. Considering the two atom-cavity subsystems driven by a Raman interaction, analytical solutions are obtained. Subsequently, the entanglement evolution between the two atoms is studied, and it is shown that

the entanglement can be stored by switching off the Raman coupling. By monitoring the radiation field, the entanglement between the two atoms can be enhanced.

Bayesian reconstruction of quantum states: a Markov chain Monte Carlo approach

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(oral, section C)

The tomographic reconstruction of quantum states represents an important laboratory tool in both quantum optics and quantum information alike. A full analysis of the experimental data, however, should also answer important questions regarding error-bars on the estimation of the state parameters, possible correlations amongst the parameters and error-propagation when using the reconstructed state for further calculations of quantities such as the purity of the state or amount of entanglement. To his end, we present a Bayesian data analysis scheme known as the Markov chain Monte Carlo (MCMC) to determine the error-bars on the estimated state parameters. The analysis returns a probability distribution, known as the posterior distribution, which contains all of the relevant statistical information concerning the errors on the reconstructed parameters. In addition, the MCMC returns a set of probability distributions on each individual parameter which corresponds to the marginalized posterior distribution for that parameter. In this talk, the basic principles of Bayesian analysis will be presented with a focus on the direct application to the problem of quantum state reconstruction. The MCMC numerical technique will also be presented. As a test case, the reconstruction of a non-Gaussian state, namely, a phase-diffused squeezed state will be demonstrated as well as the utility of the Markov chain in the calculation of the state purity. Finally, the application of the Bayesian-MCMC method to higher dimensional systems, including the reconstruction of a phase-diffused entangled state and the reconstruction of the density matrix will be presented.

Emergence of quantum indeterminacy from special relativity

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(oral, section G)

It is shown that the single-particle quantum theory with fundamental indeterminacy based on complex probability amplitudes undergoing linear superposition principle is an inevitable consequence of special relativity with the principle of relativity extended to superluminal observers.

Nonlocality of a single particle

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(oral, section G)

One of the most curious features of quantum physics is nonlocality. Loosely speaking, this means that measurements performed on one part of a system can instantaneously influence another part, even though it may be a long distance away. While widely accepted for multiparticle systems, there has been some debate about whether it also applies to a single particle. The problem is that reference states are required to measure Bell's inequalities for single particle states

and this opens the door to the possibility that any observed nonlocality is due to the reference states themselves rather than the single particle. I will discuss a scheme that aims to overcome this objection, by using completely independently prepared reference states. I will also discuss some of the interesting implications of single particle nonlocality. In particular, I will highlight how it changes when observed by a Lorentz boosted observer and the consequences this has for physically meaningful phenomena such as superconductivity.

P, C and T for trully neutral particles

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(oral, section G)

We present a realization of a quantum field theory, envisaged many years ago by Gelfand, Tsetlin, Sokolik and Bilenky. Considering the special case of the (1/2,0)+(0,1/2) field and developing the Majorana construct for neutrino we show that fermion and its antifermion can have the same intrinsic parities. The construct can be applied to explanation of the present situation in neutrino physics.

Heralded preparation and distillation of entangledlight

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(oral, section C, **invited** *)*

In this talk, we will be concerned withthe heralded preparation of entangled light, using ideas thatbring together continuous-variable

and discrete-variableapproaches [1]. Instances of detector and process tomography willbe discussed. We elaborate on directly measurable criteria forentanglement, generalizing insights of ref. [2]. These methodswill be used in new schemes for distilling entanglement, beyondref. [3], as an ingredient for feasibly preparing long-distanceentanglement. (Experimental work is being done by Ian Walmsley'sgroup in Oxford).

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Continuous-variable quantum key distribution in fibers and free space

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(oral, section F)

Quantum key distribution (QKD) is the process of establishing a secret shared key between two parties, traditionally named Alice and Bob. The security is based on the laws of quantum mechanics, whereas in classical schemes security relies only on the unproven lack of efficient mathematical algorithms. We have developed a continuous-variable QKD protocol which is suitable for atmospheric transmission as well as for fiber channels. We employ a local oscillator to perform optical homodyne detection of weak coherent signal states. In the free space experiment, Alice utilizes polarization states to combine signal and local oscillator in a single beam. As a consequence, Bob's detection is very efficient and perfectly shielded against any stray light. We have experimentally demonstrated the feasibility of this protocol over a distance of 100m on the roof of the Max Planck Institute in Erlangen [1]. As the next step, we are now establishing a link of length 1.5km between the Max Planck Institute and the University computer center. In fiber channels, we experimentally demonstrate continuous variables QKD over a short distance. This is the first fiber-based implementation of the no-switching protocol [2,3], i.e. simultaneous detection of both conjugate quadratures. Furthermore, we witness effective entanglement according to [4].

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Persistent entanglement of two coupled SQUID rings in the quantum to classical transition

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(oral, section D)

We explore the quantum-classical crossover of two coupled, identical, superconducting quantum interference device (SQUID) rings. The motivation for this work is based on a series of recent papers. In [1] we showed that the entanglement characteristics of chaotic and periodic (entrained) solutions of the Duffing oscillator differed significantly and that in the classical limit entanglement was preserved only in the chaotic-like solutions. However, Duffing oscillators are a highly idealised toy model. Motivated by a wish to explore more experimentally realisable systems we extended our work in [2,3] to an analysis of SQUID rings. In [3] we showed that the two systems share a common feature. That is, when the SQUID ring's trajectories appear to follow (semi) classical orbits entanglement persists. Our analysis in [3] was restricted to the quantum state diffusion unravelling of the master equation - representing unit efficiency heterodyne detection (or ambi-quadrature homodyne detection). Here we show that very similar behaviour occurs using the quantum jumps unravelling of the master equation. Quantum jumps represents a discontinuous photon counting measurement process. Hence, the results presented here imply that such persistent entanglement is independent of measurement process and that our results may well be quite general in nature.

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Detector tomography

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(oral, section C)

Most quantum information applications both computational and cryptographic, rely on a certain knowledge of the measurement apparatuses involved. More importantly quantum state tomography and state preparation rely heavily on the quality of the detector. As quantum technology makes striking advances, detectors are becoming complex and elaborate calling for a black box approach to their characterization. Obtaining the full description of a detector is therefore crucial but it is typically based on partial calibrations or elaborate models. Here we present the first experimental detector tomography which achieves a full characterization using minimal assumptions. Building on previous descriptions of detector tomography [2, 3], we use methods of convex optimization to find the operators closest to the experimental data for two detectors. The first one is an avalanche photodiode and the second one is a photon-number-resolving detector able to detect up to 8 photons. We also present results on practical detector tomography with phase sensitive detectors. In particular we explain the methods involved in the characterization of weak-homodyning detectors.

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Tests of multimode quantum non-locality with homodyne measurements

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(oral, section B)

We investigate the violation of local realism in Bell tests involving homodyne measurements performed on multimode continuous-variable states.By binning the measurement outcomes in an appropriate way, we prove that the Mermin-Klyshko inequality can be violated by an amount that grows exponentially with the number of modes. Furthermore, the maximum violation allowed by quantum mechanics can be

attained for any number of modes, albeit requiring a quantum state that is rather unrealistic. Interestingly, this exponential increase of the violation holds true even for simpler states, such as multipartite GHZ states. The resulting benefit of using more modes is shown to be significant in practical multipartite Bell tests by analyzing the increase of the robustness to noise with the number of modes. In view of the high efficiency achievable with homodyne detection, our results thus open a possible way to feasible loophole-free Bell tests that are robust to experimental imperfections. We provide an explicit example of a three-mode state (a superposition of coherent states) which results in a significantly high violation of the Mermin-Klyshko inequality (around 10 %) with homodyne measurements.

Quantumness tests and witnesses in the tomographic-probability representation

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(poster)

A boundary between quantum and classical worlds is rather difficult to draw precisely, while the problem of their distinguishing is getting more important than it was hardly ever before. Though there exist different ways to check the classicality of bipartite system, e.g., by employing entropy relations or Bell inequalities, the quantumness of a single system seems to be more complicated question. The simple approach to quantumness tests of a single system is developed in [1]. According to the criterion proposed, quantum or classical properties of a system state are associated with measuring some specific observables such that there exist certain inequalities which hold true in classical domain and are violated in quantum domain. Violation of the inequalities is considered as a quantumness witness of the system state. Since both classical and quantum states can be described by fair probability distributions, the question arises itself how does this criterion differ classical and quantum states given by their probability distributions. In the paper, the qubit case is considered in detail. A general family of quantumness witnesses is inroduced, with witnesses being operators depending on an extra parameter. It is also predicted what kind of experiment one should make to test the quantumness of a qubit state specified by its tomogram. Spin tomograms and dual spin tomographic symbols are used to study qubit examples and the test inequalities which are shown to satisfy simple relations within the framework of the standard probability theory. The discussion is also presented how to extend the analysis of quantumness tests given for qubits to systems with continuous variables, e.g., for photon quadrature components.

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Polarisation squeezing and entanglement in standard and photonic crystal fibres

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(poster)

Optical fibres have proven to be excellent sources for the production of nonclassical states of light. We have used a standard optical fibre and a robust and simple single-pass setup [1] to generate what is to our knowledge a record polarisation squeezing of -6.8 $\pm$ 0.3dB in an optical fibre [2]. Furthermore, two of these sources have been used to create highly entangled bipartite continuous variable polarisation states [3]. We also investigate the generation of polarisation squeezing in photonic crystal fibres (PCF) as they can be tailored to have an high effective nonlinear Kerr effect and little excess noise.

However, thus far they have shown some drawbacks to standard fibres when using the single-pass setup [4]. In order to reduce these problems we are investigating different kinds of PCFs which have improved dispersion properties while holding the promise of minimized phonon-photon coupling [5]. Additionally a novel method to produce polarisation squeezing was developed. By using two pulses of equal polarisation counter propagating on the same fibre axis and overlapping them after the PCF, we generated a maximum squeezing of -3.9 $\pm$ 0.3 dB and an anti-squeezing of 16.8 $\pm$ 0.3dB [6]. The purity of this squeezed states is more than three times higher than in a standard fibre. By exploiting both polarisation axes of the PCF we can generate two independent polarisation squeezed beams that can be used to create polarisation entanglement.

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Quantum random number generator using homodyne detection

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(oral, section F)

The production of truly random numbers has become incredibly important for quantum key distribution systems. A popular method to produce such truly random numbers is by exploiting the intrinsic randomness of quantum phenomena. At the moment most of these quantum random number generators (QRNG) rely on single photon sources and detectors. We present a method which uses homodyne detection and takes advantage of the continuous variable nature of the signal to produce a reliable and fast QRNG with a simple setup. The numbers are generated by measuring the probability distribution of the incoming signal, dividing it into equal segments (i.e. same sample size/segment) and assigning the values in each segment a certain bit combination. We mainly carried out measurements with a quantum noise limited beam as this allowed the simplest setup. However, we also investigated squeezed and anti-squeezed signals for comparison reasons. We applied different test suites, such as the common and popular Diehard and Dieharder test suites, to examine their randomness. Excellence performances in all tests have been observed so far. We have also developed a technique to constantly check the purity of the state during the measuring process which in turn allows us to prevent an eavesdropper from controlling the random numbers. This is an advantage to other QRNG and is to our knowledge the first time such a scheme has been introduced in that context. At the moment the numbers are produced at a speed of roughly 12 Mbit/s but with a few improvements the speed can easily be increased to 50 Mbit/s or even higher.

X-entanglement: the non-factorable spatio-temporal structure of biphoton correlation

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(oral, section D, **invited** *)*

Parametric down-conversion (PDC) is probably the most efficient and widely used source of entangled photon pairs, which have been employed in several successful implementations of quantum communication and information schemes. At the very heart of such technologies lies the quantum interference between photonic wave functions, which depends crucially on the spatio-temporal mode structure of the photons. In this work, the issue of controlling and tailoring the biphoton spatio-temporal structure is addressed from a peculiar and novel point of view, that is, the non factorability in space and time of the PDC biphoton entanglement. The idea is driven from recent investigations in nonlinear optics, which outlined how in nonlinear media the angular dispersion relations impose a hyperbolic geometry involving temporal and spatial degrees of freedom in a non-factorable way. The wave object that captures such a geometry is the so-called X-wave (the X being formed by the asymptotes of the hyperbola). In this work, we turn our attention to the genuine quantum level, investigating the spatio-temporal structure of the biphoton cross-correlation. We shall demonstrate that a X-geometry emerges in this microscopic context as well. The PDC entanglement has been to date investigated mostly either in a purely temporal or spatial frameworks. Our approach, based on the non-factorability in space and time of the state, will point out a key element of novelty, i.e. the possibility of tailoring the temporal bandwidth of the biphotons by manipulating their spatial degrees of freedom. In particular, by resolving their near-field positions, we will show that the X-structure opens the access to an ultra-broad bandwidth entangled photonic source, with a temporal localization in the femtosecond range. Such an extreme localization can be used to increase the sensitivity of high precision measurements e.g. in the protocol of clock synchronization.

PDC correlations for quantum imaging

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(oral, section D, **invited** *)*

The possibility of manipulating quantum states of light has paved the way to quantum technologies. Among them very interesting achievements derive from exploiting quantum correlations for innovative imaging processes. In this talk, after a general review on the subject, I will present most recent experimental results and, in particular, differential quantum imaging.

Volume thresholds for fault tolerance

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(oral, section F)

The standard approach to quantum fault tolerance is to calculate error thresholds on basic gates in the limit of arbitrarily many concatenation levels. In contrast this paper takes the number of qubits and the target implementation accuracy as given, and provides a framework for engineering the constrained quantum system to the required tolerance. The approach requires solving the full dynamics of the quantum system for an arbitrary admixture (biased or unbiased) of Pauli errors. The inaccuracy between ideal and implemented quantum systems is captured by the supremum of the Schatten k-norm of the difference between the ideal and implemented density matrices taken over all density matrices. This is a more complete analysis than the standard approach, where an intricate combination of worst case assumptions and combinatorial analysis is used to analyze the special case of equiprobable errors. Conditions for fault tolerance are now expressed in terms of error regions rather than a single number (the standard error threshold). In the important special case of a stochastic noise model and a single logical qubit, an optimization over all 2×2 density matrices is required to obtain the full dynamics. The complexity of this calculation is greatly simplified through reduction to an optimization over only three projectors. Error regions are calculated for the standard 5- and 7-qubit codes. Knowledge of the full dynamics makes it possible to design sophisticated concatenation strategies that go beyond repeatedly using the same code, and these strategies can achieve target fault tolerance thresholds with fewer qubits.

Space, time and quantum nonlocality

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(oral, section G, **invited** *)*

Quantum nonlocality, i.e. the fact that the outcomes of some measurements on some quantum systems can't be described using only localvariables, puts serious doubts on the completeness of today's physics notions of space and time. We'll discuss some aspect of this conflict.

Preparation of distilled and purified continuous-variable entangled states

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(oral , **invited** *)*

The distribution of entangled states of light over long distances is a major challenge in the field of quantum information. Optical losses, phase diffusion and mixing with thermal states lead to decoherence and destroy the non-classical states after some finite transmission-line length. Quantum repeater protocols, which combine quantum memory, entanglement distillation and entanglement swapping, were proposed to overcome this problem. Here we report on the experimental demonstration of entanglement distillation in the continuous-variable regime [1] and its tomographic characterization . Entangled states were first disturbed by random phase fluctuations and then distilled and purified using interference on beam splitters and homodyne detection. In contrast to previous demonstrations of entanglement distillation in the complementary discrete-variable regime, our scheme achieved the actual preparation of the distilled states, which might therefore be used to improve the quality of downstream applications such as quantum teleportation. The output states were characterized by means of a novel two mode tomography technique providing the ability of state reconstruction.

[1] B. Hage, A. Samblowski, J. DiGuglielmo, A. Franzen, J. Fiurášek and R. Schnabel, Nat. Phys. 4, 915 (2008).

Understanding and uses of cold atom 'cat states'

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(poster)

The exploration of possible applications of quantum states has only just begun. Already promising applications in understanding fundamental physics, phase transitions and quantum technologies such as precision measurements and quantum computing have been made. By theoretical investigation we have shown how different types of 'cat states' with different robustness can be made. We then show how these can be used to understand their nature and used to make precision measurements of rotation. The system comprises of a quasi-1D loop that is either continuous with a barrier, or an optical lattice, that can be rotated. This goes beyond mean field analysis by studying small systems at a microscopic level using second quantized formalism.

Measurement of angle uncertainty of momentum correlations and spectral characteristics of the photons generated in parametric fluorescence

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(poster)

Parametric fluorescence is very often used in imaging experiments, also referrred to as ghost imaging. In these applications, the uncertainty in the determination of angles of emission of signal and idler photons limits the spatial resolution of the image. This uncertainty defines the volume in space behind the crystal, where signal and idler photons are partially correlated. The uncertainty in the angular coordinates is caused by the imperfect momentum conservation of the signal, idler and pump photons.Many parameters like divergence of the pumping beam, width of the pumping spectrum, size of the crystal influence this uncertainty. We have developed a numerical model involving these parameters and yielding the angular and spectral characteristics of the signal and idler fields. The obtained numerical results are compared with the experimental data.We used three different methods to measure the angular uncertainty. First, a scan with the circular aperture has been used. This method has been combined with the measurement of the fourth-order autocorrelation function in the Hong-Ou-Mandel interferometer. In the second approach, a scan by an edge has been applied instead of a circular aperture. The third method uses an intensified CCD camera. The dependence of the size of angular uncertainty on the divergence of the pumping beam has been measured.

Non-classical nature of a quantum flux in a double SQUID

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(poster)

We investigate the non-classical nature of a quantum flux in a double SQUID which is a superconducting ring interrupted by a dc-SQUID. This system is equivalent to an anharmonic oscillator with a time-dependent frequency. A rapid change of the magnetic flux in the dc-SQUID abruptly changes the Josephson frequency, leading to the nonadiabatic mixing of the quantum states for a quantum flux in a double SQUID. As a result, squeezing of the quantum flux occurs due to the Bogoliubov transformation between eigenstates at different times. We perform numerical calculations for the quantum state evolution of the quantum flux within a harmonic approximation, taking account of the nonadiabatic effect, and found that the state distribution has a super-Poissonian character that is a signature of flux squeezing.

Continuous variable entanglement in open quantum systems

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(poster)

In the framework of the theory of open systems based on completely positive quantum dynamical semigroups [1,2], we study the continuous variable entanglement for a system consisting of two independent harmonic oscillators interacting with a general environment. We solve

the Markovian master equation for the time evolution of the considered system and, by using Peres–Simon necessary and sufficient criterion for separability of two-mode Gaussian states [3,4], we describe the generation and evolution of entanglement in terms of the covariance matrix, for a correlated coherent initial state. We show that for certain values of diffusion and dissipation coefficients describing the environment, the state keeps for all times its initial type: separable or entangled. In other cases, entanglement generation, entanglement sudden death or a periodic collapse and revival of entanglement take place [5]. In particular, we describe the dynamics of entanglement in terms of the squeezing coefficient of the initial Gaussian state and the temperature of thermal bath. We analyze also the time evolution of the logarithmic negativity, which characterizes the degree of entanglement of the quantum state.

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[3] A. Peres, Phys. Rev. Lett. 77, 1413 (1996).
[4] R. Simon, Phys. Rev. Lett. 84, 2726 (2000).
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Wave-particle duality of large molecules revealed

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(oral, section E)

Molecular interferometry has proven to be a suitable tool for testing the wave-particle duality of large, heavy and hot molecules. We report on a new detection scheme for molecular interferometry: the near-field interference pattern is deposited onto a detection surface, which is subsequently imaged using various microscopic techniques. Scanning tunneling microscopy even allows to image every single molecule with nanometer resolution within the interference pattern, revealing the wave-particle duality in its clearest form. First interferograms of C60 molecules deposited onto reconstructed Si(111)7x7 are presented. This method is not only intuitive and most sensitive, but also intrinsically scalable to larger molecules or clusters. Alternative detection schemes using AFM or fluorescence microscopy will be discussed.

The transactional nature of quantum information

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(oral, section F)

Quantum information is traditionally measured by the von Neumann entropy, which is a thermodynamic measure. The von Neumann entropy for a pure state is zero, it is independent of the receiver and it has some characteristics that are intuitively unreasonable. For example, the Bell state is a pure state with zero entorpy, but its components are in mixed state and they have non-zero entropy. In classical communications theory, information is a property that is associated with the surprise the received message has for the recipient. From this perspective, the information associated with an unknown pure state should be non-zero. The idea of zero entropy for an unknown pure state is in accord with the perspective that once the state has been identified, there is no further information to be gained from examining its copies. But it is not reasonable if the game being played between the sender and the receiver consists of the sender choosing one out of a certain number of polarization states (say, for a photon) and supplying several copies of it to the receiver. In this latter case, the measurements made on the copies do reveal information regarding the choice made. If the set of choices is infinite, then the 'information' generated by the source is unbounded. From the point of view of the preparer of the states, the information in the pure state is limited by the 'relationship' between the source and the receiver, and by

the precision of the receiver's measurement apparatus. If the sender chose a polarization state that the receiver's measurement apparatus was already synchronized with, the receiver could recognize the state quite readily. In this paper we consider several issues related to this transactional nature of quantum information and discuss its possible applications to computing and cryptography.

Model of extended Newtonian dynamics and Feynman's path integrals

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(oral, section G)

Newton's physics is describes macro-objects sufficiently well, however it does not describe microobjects. A model of extended Newtonian dynamics (MEND) is based on an axiomatic generalization of Newton's classical laws to non-inertial reference frames postulating the description of body dynamics by differential equations with higher derivatives of coordinates with respect to time but not only of second order ones. In that case the Lagrangian $L = L(q, \dot{q}, \ddot{q}, ..., \dot{q}^n)$ depends on higher derivatives of coordinates with respect to time and corresponds to Feynman's multiple path integrals. The kinematic state of a body is considered to be defined if n-th derivative of the body coordinate with respect to time is a constant (i.e. finite). First, kinematic state of a free body is postulated to invariable in an arbitrary reference frame. Second, if the kinematic invariant of the reference frame is the n-th order derivative of coordinate with respect to time, then the body dynamics is describes by a (n+1)-order differential equation. For example, in a uniformly accelerated reference frame all free particles have the same acceleration equal to the reference frame invariant, i.e. reference frame acceleration. These bodies are described by third-order differential equation in a uniformly accelerated reference frame.

Ostrogradsky dynamics and Feynman's transition amplitudes

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(poster)

If the existence of the minimal elementary length ℓ_0 is supposed, then the continuous analysis should be replaced by the discrete one. Therefore, the field equations should be replaced by the system of dynamical equations for the values of the field function $u(x_i, t) = q_i(t)$ at the nodes of the space lattice. If one eliminates all variables q_i beside the single one $q(t) = u(0, t)$, then there appears the infinite order differential equation corresponding to the so-called Ostrogradsky dynamics. In this case the Lagrangian $L = L(q, \dot{q}, \ddot{q}, ..., \dot{q}^n, ...)$ depends on higher derivatives of coordinates with respect to time. In generalized dynamics suggested by M. V. Ostrogradsky the motion is described by the infinite-components vector $\alpha = \alpha(q, \dot{q}, \ddot{q}, ..., \dot{q}^n, ...)$. In quantum theory the corresponding Feynman transition amplitude becomes

$$\langle\alpha_1|\alpha_2\rangle = \int D\alpha \exp(\tfrac{\imath}{\hbar} \int\limits_{t_1}^{t_2} L[\alpha]dt)$$

and contains functional integral over the higher derivatives histories. The proposed scheme can be applied to the quantum description of extended particles.

Parallel bosonic Gaussian additive noise channels with a total input energy constraint

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(oral, section F)

We study bosonic Gaussian channels with a classical noise under the physical assumption of a finite input energy. By input energy, we understand both the energy of classical signal (modulation) and the energy spent on squeezing the quantum states carrying the classical signals. We find the optimal repartition of the total input energy that maximizes the channel transmission rate given by the Holevo quantity. The energy is distributed not only between the n channel modes but also in each mode between the part used for squeezing the quantum states and the part used for classical modulation. We consider in detail one- and two-mode channels, then extend our results to n-mode channels including the limit of infinite n, thus obtaining the classical capacity of the channel. We show that above a certain threshold for the input energy we recover the optimal energy distribution given by the solution known in the case of classical channels as 'water filling'. This solution corresponds to an overall thermal state at the output of the channel. Below this energy threshold determined by the channel noise, the water filling solution is no more valid. We find another solution in the form of an implicit function. We analyze this new solution and show that it may be well described by a linear approximation. In the related report (poster) entitled 'Classical capacity of a bosonic memory channel with Gauss-Markov noise' by J. Schäfer we present an application of these ideas to a particular model of classical noise and evaluate the channel capacity.

Quantum mechanics from classical mechanics with Hilbert phase space

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(poster)

We study the relation between the mathematical structures of classical statistical mechanics on infinite dimensional phasespace and quantum mechanics. It is shown that quantum average (given by the von Neumann trace formula) can be obtained as the main term of the asymptotic expansion of Gaussian functional integral on Hilbert phase space with respect to a small parameter – dispersion of the Gaussian measure. Symplectic structure on infinite dimensional phase space plays the crucial role in our considerations. In particular, measures on Hilbert phase space should be consistent with the symplectic structure. Equations of Schrödinger, Heisenberg and von Neumann are images of Hamiltonian dynamics on Ω. Thus, in spite of all no-go theorems (including Bell's theorem) a natural prequantum model can be constructed. The pice for 'classicality' is the infinite dimension of phase space.

Prequantum classical field theory predicts violation of Born's rule

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(oral, section G)

Recently a new attempt to go beyond quantum mechanics (QM) was done – prequantum classical statistical field theory (PCSFT). The main experimental prediction of PCSFT is violation of Born's rule. The latter is only an approximative formula. We expect that it will be possible to design experiments demonstrating violation of Born's rule. Moreother, recently the first experimental evidence of violation was found in the three slit interference experiment performed by the experimental group of Gregor Weihs. It provides at least preliminary confirmation of the main prediction of PCSFT. In our approach quantum particles are just symbolic representations for 'prequantum random fields.' These prequantum fields fluctuate on time and space scales which are essentially finer than scales of QM, cf. 't Hooft's attempt to go beyond QM. In this talk we elaborate a detection model in the PCSFT-framework. In this model classical random fields (corresponding to 'quantum particles') interact with detectors inducing probabilities which match with Born's rule only approximately. Thus QM arises from PCSFT as an approximative theory.

Application of non-classicality criteria to experiments

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(oral, section A)

A quantum state is nonclassical if its Glauber-Sudarshan P function fails to be interpreted as a probability density. However, since the P function is often highly singular, the straightforward application of this definition is only feasible in special situations [1]. Therefore, different criteria have been developed. One possible solution is the examination of the characteristic function of the P function, which can reveal nonclassical effects directly. Alternatively, one can examine the violation of the nonnegativity of special matrices of moments of the quadrature operator. We compare both criteria by application to phase-diffused squeezed vacuum states [2]. We show theoretically and experimentally that these states are always nonclassical, even if the squeezing is hidden by the phase-noise. Furthermore, we take special care for the evaluation of the statistical significance of the demonstrated effects.

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imental determination of a nonclassical Glauber-Sudarshan P function, Phys. Rev. A 78, 021804(R) (2008).
[2] T. Kiesel, W. Vogel, B. Hage, J. DiGuglielmo, A. Samblowski, and R. Schnabel, *Experimental test of nonclassicality criteria for phase-diffused squeezed states*, Phys. Rev. A 79, 022122 (2009).

Feynman and squeezed states

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(oral, section G)

In 1970, Richard Feynman wrote down a Lorentz-invariant differential equation in order to understand relativistic particles with internal space-time structures. This equation can have more than 240 different solutions depending on separation of variables. It is shown that squeezed states in optics can be explained in terms of one set of those solutions. In addition, this equation can explain some of the current issues in physics including entanglement and decoherence, as well as a Lorentz-invariant form of the uncertainty principle.

Spin-squeezed atomic vapors: Is there any gain or not?

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(oral, section E)

Spin noise sets fundamental limits to the precision of measurements using spin-polarized atomic vapors, such as performed with sensitive atomic magnetometers. Spin squeezing offers the possibility to extend the measurement precision beyond the standard quantum limit

of uncorrelated atoms. Contrary to current understanding, we show that, even in the presence of spin relaxation, spin squeezing can lead to a significant reduction of spin noise, and hence an increase in magnetometric sensitivity, for a long measurement time. This is the case when correlated spin relaxation due to binary alkali-atom collisions dominates independently acting decoherence processes, a situation realized in thermal high atom-density magnetometers and clocks [1].

[1] Phys. Rev. Lett. 100, 073002 (2008).

Ultra-sensitive spin-measurements below the standard quantum limit

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(oral, section E)

We demonstrate quantum-noise-limited performance of an atom-light interface by measuring the projection noise of a thermal spin state. The thermal distribution of atoms among all Zeeman substates with the same spin is an ideal reference as quantum noise standard. It gives the same noise-scaling in atom number as a coherent spin state, which is a minimum uncertainty state. We can see a strong analogy to the use of coherent states of light for the calibration of shot-noise-limited photo-detectors. The atomic system is an elongated ensemble of about one million cold rubidium 87 atoms. It is hold in an all-optical trap which ensures a low decoherence environment. The on-resonant optical depth on-axis is larger than 50. Far detuned light pulses are used to probe the atomic state dispersively. This quantum non-demolition interaction is characterized in terms of first and second order moments of far detuned probe pulses. By measuring both moments, important information about interaction strength and destruction are obtained. As few as 700 spins can be measured with less than 20% of destruction of the atomic state. In terms of quantum noise we are able to reach the standard quantum limit. The atomic projection noise is 5.3dB above the light shot noise at about $8 * 10^5$ atoms. The sensitivity at this low destruction would suggest the capability of producing conditional spin squeezing of about 5dB. Technical noise sources are measured to be -14dB and -9dB below the projection noise level for light and atoms, respectively. The presented atom-light interface opens the door to study for example quantum-memory protocols, multipartite entanglement, or non-Gaussian continuous variable states.

Heisenberg's uncertainties and the submicrosocpic concept

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(poster)

In conventional quantum mechanics an undetermined 'wave-particle' is further substituted by a package of superimposed monochromatic abstract waves. It is this approximation that gives rise to the inequality of the wave number dk and the position dx of the package under consideration, which then results in Heisenberg's uncertainties [dx, dp] > h, since in line with de Broglie k = p / h. Submicroscopic mechanics [1] developed on the Planck scale in the real space that is constructed as a mathematical lattice of primary topological balls, called a tessel-lattice [2], operates with a particle and a cloud of excitations, called inertons, that accompany the particle at its motion through the tessel-lattice. The introduction of inertons immediately destroys the principle of uncertainty, because in the real space instead of an undetermined wave-particle we have two subsystems: the particulate cell (the particle kernel) and the inerton cloud that accompanies it. The wave function psi is treated as an image of the original field of inertia (i.e. particle's inerton cloud) defined in the real space. This deeper sub-microscopic consideration points out to the fact that the uncertainty relation deals only with one subsystem, the particle, i.e. the particulate cell. The other subsystem, i.e. the particle's inerton cloud, is not taken into account. Submicroscopic mechanics is deterministic by its nature and allows us to fill white gaps inaccessible for conventional probabilistic quantum mechanics developed on the atom scale in an abstract phase space.

[1] V. Krasnoholovets, *Submicroscopic deterministic quantum mechanics*, Int. J. Computing Anticipatory Systems 11, 164 (2002), arXiv: quant-ph/0109012.
[2] M. Bounias and V. Krasnoholovets, *Scanning the structure of ill-known spaces: Part 2. Principles of construction of physical space*, Kybernetes: Int. J. of Systems and Cybernetics 32, 7/8, 976 (2003), arXiv: physics/0212004.

The Bose-Einstein condensation and the submicroscopic concept

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(poster)

The sub microscopic approach, which is based on the structure of real physical space as the tessellation of primary topological balls [1] and the deterministic submicroscopic mechanics [2] developed in the real space, is applied for the description of Bose-Einstein condensation. A stable local deformation of the tessel-lattice, i.e. its fractal deformed cell, is treated as a canonical particle. Submicroscopic mechanics of a particle is characterised by a cloud of excitations called inertons, which represent a substructure of the particle's wave psi-function and, hence, the psi-function represents the particle's field of inertia. Conventional knowledge: in a gas of ultracold atoms with the de Broglie wavelength equals to the mead distance between them atoms begin to interact through the overlapping of their wave function, this is the essence of the coherent state. Submicroscopic mechanics states that the overlapping of inerton clouds of entities occurs much early at a higher temperature and a larger distance between atoms. The phenomenon of the whole coherent state in which the motion of all the atoms is synchronized appears when the atom's de Broglie wavelength exactly becomes equal to the distance between atoms. In this case the (n-g)-th atom emits its inerton cloud that then is fully absorbed by the n-th atom, the n-th atom emits its own cloud of inertons, which then is fully absorbed by the (n+g)-th atom, etc. In other words, the coherent exchange of inerton clouds by the atoms when an inerton cloud emitted by one atom hops to the neighbour atom and is absorbed by it has to be related to the phenomenon known as the Bose-Einstein condensation.

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[2] V. Krasnoholovets, *Submicroscopic deterministic quantum mechanics*, Int. J. Computing Anticipatory Systems 11, 164 (2002), arXiv: quant-ph/0109012.

Continuous variables quantum erasure-correcting code

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(oral, section B)

Quantum information processing relies on the robust and faithful transmission, storage and manipulation of quantum information. However, since errors are inherent to any realistic implementation, the future of quantum information systems strongly relies on the ability to detect and correct for these errors. We consider a scheme to eliminate these errors in a continuous variable (CV) quantum channel. We devise a CV quantum erasure-correcting code, which protects coherent states of light against complete erasure [1]. The scheme encodes two coherent states into a bi-partire entangled state, and the resulting 4-mode code is conveyed through 4 independent channels that randomly erases the signal. We show experimentally that the transmitted state can be corrected by performing a syndrome measurement followed by a corrective transformation. The error correction can be deterministic if the location of the error is known and only a single channel has been affected. If the location of the erasure is unknown and more than one channel has been corrupted, the signal can be recovered probabilistically where the transmitted state is either kept of discarded depending on whether an error was detected in the syndrome measurement. We have experimentally demonstrated both strategies and obtained transmission fidelities beyond what is possible by classical approaches.

[1] J. Niset et al., Phys. Rev. Lett. 101, 130503 (2008).

Conditional preparation of arbitrary superpositions of atomic Dicke states

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(poster)

We propose an experimentally accessible procedure for conditional preparation of highly non-classical states of collective spin of an atomic ensemble. The quantum state engineering is based on a combination of QND interaction between atoms and light previously prepared in a non-Gaussian state using photon subtraction from squeezed vacuum beam, homodyne detection on the output light beam, and a coherent displacement of atomic state. The procedure is capable of non-deterministic preparation of a wide class of superpositions of atomic Dicke states. We present several techniques to optimize the performance of the protocol and maximize the trade-off between fidelity of prepared state and success probability of the scheme.

The geometrical properties of entangled states

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(oral, section D, **invited** *)*

Entanglement has enjoyed a special role in physics ever since the famous discussion between Einstein and Bohr about their Gedanken experiments: a pair of sub systems was postulated in which the ability to infer the values of two conjugate observables of the second sub system based on observations of the first sub system is less uncertain than the uncertainty allowed for by quantum mechanics in the case of an isolated subsystem. Such counter intuitive states exhibit correlations between two sub-systems of a very non-classical nature and in turn lead to fundamentally new interactions and applications in the field of quantum information [1, 2].
Launched by this essential role in quantum information processing, a great number of experiments have investigated the production of entangled states of photons, both in discrete variable (DV) regime [3] and in continuous variable (CV) regime [4]. For a long time DV and CV states were investigated separately from each other. Recently, the developments of quantum information applications such as quantum cryptography, quantum computations and others, exploit both 'worlds' — discrete and continuous, as far as both have some advantages [5-10]. This stimulates further theoretical and experimental research aimed to unify the 'worlds'.
We found an interesting similarity between DV and CV states, based on the rotational invariance of the bipartite states. We theoretically

and experimentally demonstrate that two–mode CV entangled states show angular correlations which are very similar to those of the triplet Bell states. In this sense we show a continuous variable analogy to the triplet Bell states.

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Unconditionally secure protocol for long-distance continuous-variable QKD with discrete modulation

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(oral, section F)

We introduce a new continuous-variable quantum key distribution protocol combining a discrete modulation and reverse reconciliation. This protocol is proven unconditionally secure and allows the distribution of secret keys over long distances. Hence it presents the same advantages in terms of security and distance as most discrete-variable protocols while relying on homodyne detection instead of photon counting, which makes it very practical. These performances are achieved by working in a low signal-to-noise ratio regime where 1) Alice and Bob can efficiently extract information from their correlated data thanks to low rate, capacity-achieving error correcting codes 2) one can (tightly) bound Eve's information thanks to extremality properties of Gaussian states.

Some topics in quantum imaging

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(oral, section D, **invited** *)*

So far, parametric down-conversion (PDC) demonstrated the most efficient room-temperature source of entangled photon pairs, employed in successful implementations of quantum communications and quantum imaging schemes. The first part of the talk will illustrate the opportunity of applying PDC to the detection of faint objects with a sensitivity beyond the standard quantum limit. The second part of the talk will address the topic usually called 'ghost imaging.' Due to the fact that this technique can be implemented not only using a quantum source such as PDC, but also by standard classical sources such as pseudo-thermal light, and due to its non-invasive character, this approach may offer some interesting applicative perspective.

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Angular momentum coherence and squeezing

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(poster)

A simple, and elegant geometrical representation is developed to describe the concept of coherence and squeezing for angular momentum operators. Angular momentum squeezed states were obtained by applying Bogoliubov transformation on the angular momentum coherent states in Schwinger representation [1]. We present the geometrical phase space description of angular momentum coherent and squeezed states and relate with the harmonic oscillator. The unique feature of our geometric representation is the portraying of the expectation values of the angular momentum components accompanied by their uncertainties. The bosonic representation of the angular momentum coherent and squeezed states is compared with the conventional one mentioning the advantages of this representation of angular momentum in context of coherence and squeezing. Extension of our work on single mode squeezing to double mode squeezing is presented and compared with the single mode one. We also point out the possible applications of the geometrical representation in analyzing the accuracy of interferometers and in studying the behavior, dynamics of an ensemble of quantum-mechanical two-level systems and its interaction with radiation.

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Super-fast cooling of trapped particles

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(oral, section E)

We propose a novel method for cooling systems of harmonically trapped particles with controllable coupling, such as trapped ions or atoms having motional degrees of freedom which may be coupled at will to the ions' internal energy level. By optimizing the timing of couplings between the two, we accelerate the transfer of energy between them and achieve cooling rates significantly faster than the trap frequency and with lower final temperatures. The proposed method is shown to be robust in face of the various sources of noise expected in a real-world implementation. We believe this approach to be applicable in a wide variety of systems including mechanical oscillators for which the proposed method can break the temperature limit imposed by the finite Q factor.

A polynomial method to study the entanglement of pure N-qubit states

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(poster)

We present a new way to study the entanglement of pure N-qubit states. This method is based on associating a quantum state with a polynomial. The roots of this polynomial contain information about the entanglement of the state. Besides allowing to detect entanglement, our method makes possible an easy construction of fully N-qubit entangled states.

Experimental possibilities in view of the probability representation of quantum mechanics and quantum optics

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(oral, section G)

Review of the tomographic probability representation of conventional quantum mechanics where fair probability distributions are used as alternatives of the wave functions or density matrices is presented for both qudits and systems with continuous variables. New notions which naturally appear in the probability representation of quantum mechanics are discussed. A set of the standard and new uncertainty relations appropriate for direct experimental checking by using homodyne photon detector is proposed. The Schroedinger-Robertson uncertainty relation is considered in detail as a particular relation to be checked by measuring optical tomogram of the photon state and to be used as the accuracy test in available experimental data. Connection of photon statistics for multimode fields with optical tomograms and quadrature uncertainty relation is clarified. The observation of appearance of negative or complex values of the functions (multivariable Hermite polynomials), in terms of which the photon distribution is expressed, for quadrature variances and covariances violated the uncertainty relations is presented.

Photon statistics of squeezed light in the probability representation of quantum optics

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(oral, section A)

Expression for the photon distribution function of squeezed states of light in terms of symplectic and optical tomograms of one-mode and

multimode electromagnetic field states is obtained. The properties of variances and covariances of the photon quadratures in the multimode Gaussian field states are associated with the characteristic functions for the photon number tomograms. The entanglement phenomenon is formulated in terms of factorization of the symplectic and photon number tomograms and characteristic functions corresponding to these tomograms. The cumulants associated to the photon number tomograms of the Gaussian states are studied. The connection of the positivity of the photon number tomograms with the quadrature uncertainty relations is established.

Quantum inequalities for tomographic entropies of qudit states

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(oral, section A)

Spin tomograms of qubit and qudit states considered as standard classical probability distributions are used to introduce the notion of tomographic entropies. New inequalities for tomographic entropies are obtained in view of quantum Fourier transform. The inequalities obtained are used to find the connection of the entropic uncertainty relations with the dimension of qudit Hilbert space. The case of infinite dimensional Hilbert space and the tomographic uncertainty relations for the photon quadratures in the space are discussed as a generalization of the known entropic uncertainty relations.

Continuous variables quantum information with light

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We present a sample of research in continuous variables quantum information based on quantum optics. Namely we deal with analysis of new methods for generation of large 'Schroedinger Cat states' - squeezed superposed coherent states, investigation of relationship between non-classicality and entanglement, search for sufficient resources for universal quantum computation, and purification of phase information.

Consistent entanglement measures for two-mode Gaussian states

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(oral, section B)

We evaluate a Gaussian entanglement measure for an arbitrary two-mode Gaussian state of the quantum electromagnetic field in terms of its Bures distance to the set of all separable Gaussian states. We here exploit our recent derivation of the Uhlmann fidelity between two-mode Gaussian states. The principal idea of our treatment is to use the optimal pure-state decomposition of a two-mode Gaussian state previously written in [1]. It turns out that the Gaussian degree of entanglement measured by the Bures distance is consistent to the exact entanglement of formation for two-mode Gaussian states.

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Experimental entanglement distillation of mesoscopic quantum states

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(oral, section D)

One of the main tasks of quantum communication is to transmit quantum information between distant sites robustly and faithfully. Quantum information can be send over large distances by using quantum teleportation. However, the success of such protocols depends strongly on the degree of entanglement shared by the two communicating parties. Unfortunately, such entangled states are very sensitive to the unavoidable and devastating interaction with the environment. For instance, a free space channel exhibits a wide variety of deleterious effects such as non-stationary absorption, scattering etc. These time dependent fluctuations of the attenuation factor result in non-Gaussian noise which will destroy the entangled states. Fortunately, due to the non-Gaussian character of the noise, it is possible to recover the corrupted entanglement by simple Gaussian operations utilizing a beam splitter, homodyne detection and feed forward. We demonstrated a simple method of distilling entanglement from single copies of states that have undergone attenuation in a lossy channel with a varying transmission [1]. The distillation protocol is implemented by performing a weak measurement based on a beam splitter and a homodyne detector and post selection. The protocol is successfully demonstrated for a discrete transmission channel and a semi-continuous transmission channel. We found that the degree of Gaussian entanglement was substantially increased by the action of distillation for the noise channels. This opens new possibilities for entanglement distribution in noisy atmospheric environments.

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Extra phase noise from phonon scattering degrades quantum correlations in nonlinear systems

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(oral, section B)

Recent experiments with Optical Parametric Oscillators have shown that an unpredicted extra noise on the phase of the fields reduces the level of squeezing or quantum correlations. In some cases, it can hinder the attempts to observe entanglement in those systems. It is one of the main reasons why signal and idler entanglement above threshold remained unobserved for almost 20 years after its initial prediction. We show that this extra noise can be explained by phonon scattering of the fields' carrier frequencies. In this Brillouin process, light that is scattered from the intense fields acts as an extra noise source for the sidebands, where squeezing is generally observed. We present a model that successfully describes the measured dependence of the excess noise with the intracavity power, beam waist, and crystal temperature. Good agreement with the observed results is obtained. Adding this noise source to the analysis of the quantum features in the OPO above threshold, we could explain our recent results in the quest for tripartite entanglement in this system. Our OPO consists of a triply resonant cavity with a type-II KTP crystal, pumped above threshold by the second harmonic of a Nd:YAG laser.

We can make the complete reconstruction of the covariance matrix for pump, signal, and idler fields and perform an entanglement test using the symplectic eigenvalues of the covariance matrix under a partial transposition operation. The results present good agreement with the model, and show that this excess noise hinders the observation of tripartite entanglement in the system. Understanding this noise is a crucial step towards the experimental demonstration of this entanglement and for the improvement of quantum features in the continuous variable domain in Quantum Optics.

Dynamic entanglement and separability criteria for quantum computing bit states

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(oral, section F)

Since 1935 when Erwin Schrödinger used the word Verschränkung and Einstein, Podolsky, Rosen and Bohm discussed on the EPR correlation, entanglement has been a controversial issue in physics not yet perfectly solved. However, in recent couple of decades, technological applications especially quantum cryptography and quantum computing have widely been challenged. In this paper a theoretical framework is demonstrated to evaluate the entanglement of bit states in quantum computing. Separability of general polynomial superposition of Hilbert space basis vectors is discussed, and criteria in amplitude as well as in phase are derived [1]. Starting from a completely factorized totally separable (TS) 3 bit system, controlled not (CN) and controlled rotation (CR) gates are shown to interlink the bits into totally semi-separable (TSS) states, and controlled controlled not (CCN) and controlled controlled rotation (CCR) further into partially semi-separable (PSS) states, but controlled phase shift (CPS) keeps the separability. Furthermore, the selection of measurement mode external to the quantum system is incorporated in the polynomial using Kronecker delta, introducing the concept of dynamic entanglement where the sum of squared probability amplitudes apparently goes up beyond 1. With this, some process of wavefunction collapse upon measurement would be understood as the manifestation of the dynamic entanglement. A firefly in a box model is employed to show a pure state of ontological uncertainty [2], which is in the dynamically entangled state.

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Quantum dot realization of quantum information processing

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(oral, section F, **invited** *)*

The freedom of design and control of nanostructures is a realistic target in the fields including physics, engineering, chemistry, biology and medicine in our era. Accordingly, we are entering into the regime where quantum mechanical phenomena play the major roles, not only in the research activity but also in our daily life. This talk would focus on the possible contribution of quantum dots in quantum computing and quantum cryptography. Starting from a brief review of the downsizing trend of devices, principles of quantum computing and quantum cryptography, the choice of materials, the choice of physical actions and properties are discussed. Then, semiconductor quantum dots are explained with respect to the structure, size and shape. Band gap engineering is provisioned to artificially generate photons of desired energy, and also to prepare dipoles and quadrupoles for useful interactions. The fabrication technology is briefly shown too. Furthermore, artist's structures of future quantum computing circuits of quantum dots are demonstrated with reference to conventional electrical as well as optoelectronic integrated circuits. Lastly, the power of quantum computing and the difficulty in achieving the unlimited security by quantum cryptography will be discussed.

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Estimation of photonic multipolar coupling ranges among quantum dots on the basis of time-energy uncertainty

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(poster)

The manifestations of Heisenberg time-energy uncertainty principle may be classified into two types, one for quanta creation and the other for Fourier transformation. This paper gives a real use of the former type of uncertainty for nanostructure circuit design consideration. The range of virtual as well as real photons mediating interactions among nano-structures is estimated in a product of photon lifetime and its velocity, as in the meson exchange model for nucleon [1]. This gives a new vista for the near field interactions of electric nature in solid, especially for the nonradiative internal energy transfer that may be called as resonance dynamic multipole-multipole interaction (RDMMI) [2]. This photon exchange model has not been familiar in physics of solids, mainly because the range of the mediating photon of significant energy was not long enough to cover the distance of usual concern, e.g. size of devices in conventional integrated circuits. However, in our nanoscale structures, this type of understanding is becoming indispensable. Therefore, the length of the transition dipole is deduced from the 0.3 meV fine structure in our micro-photoluminescence spectra of an indivisual coupled GaAs

asymmetric quantum dots [3]. Various multipoles and their potentials are estimated employing the dipole length. Then, on the basis of the time-energy uncertainty, the ranges and lifetimes of the RDMMI are derived and plotted, together with the spatio-temporal consideration and a provisional structure of quantum circuits.

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Exact dynamics of entanglement and entropy in structured environments

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(oral, section D)

Entanglement and mixedness are two different physical quantities characterizing the degree of non-classicality of a quantum state. Hence, understanding the interplay between them is crucial for grasping the nature of quantum correlations in multipartite systems. For example, the study of maximally entangled mixed states, namely the states with a maximum amount of entanglement for a given degree of purity, represents an important contribution in this direction. In [1] we have studied the entanglement dynamics of two qubits interacting with a common zero temperature non-Markovian reservoir. We have presented interesting features of the dynamics, including sudden death and resurrection of entanglement, for a Bell-like state with two excitations. The dynamics of the qubits in a common structured reservoir in the case of one excitation was studied in [2], where a strategy to protect entanglement via quantum Zeno effect is proposed. Here, we investigate the connection between mixedness and entanglement addressing two different problems. We study how the two qubits-entanglement dynamics changes with the degree of purity of the initial state, which is an extended Werner-like state. We compare entanglement and entropy dynamics for Bell-like states, finding remarkable correlation between these two quantities. Our results are particularly interesting when sudden death and revivals of entanglement occur, providing a deeper comprehension of these phenomena.

[1] L. Mazzola, S. Maniscalco, J. Piilo, K.-A. Suominen and B. M. Garraway, arXiv:0812.3546, accepted for publication by Phys. Rev. A.
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One-way quantum computation in the optical frequency comb

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(oral, section F)

The invention of one-way quantum computing introduced a new paradigm for quantum information processing, whereby the unitary evolution required in the traditional circuit model is replaced by measurements on a highly entangled cluster state. In this model, quantum information exists virtually in the cluster state and is manipulated through local adaptive measurements. The measurement backreaction on the entangled state induces dynamics on the encoded quantum information and thereby quantum computation. Much of the experimental difficulty in performing a quantum computation has thus been concentrated into the creation of the cluster state in the first place. Practical and scalable methods are therefore desired. Here, we propose a method for creating large cluster states efficiently in a top-down, single-shot fashion. This method uses a single optical parametric oscillator (OPO) driven by a multifrequency pump. With an appropriate nonlinear medium and a pump beam with the right frequency content, the modes of the optical cavity (an optical frequency comb) will encode a large square-lattice continuous-variable cluster state. Remarkably, this can be achieved using just a single OPO and with a constant number of pump frequencies, regardless of the size of the cluster! Compared to existing proposals that use lots of optical elements to build up the cluster piece-by-piece, these modest experimental requirements, together with the naturally large set of cavity modes, mean that this approach has strong potential for scalability [1].

[1] Phys. Rev. Lett. 101, 130501 (2008); arXiv:0811.2799.

Localizable entanglement in three coupled spins in a thermal state

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(poster)

Notwithstanding the relevance of multipartite entanglement in different physical scenarios, its definition and measurement is still an open and debated problem. Very recently, in order to quantify the bipartite entanglement contained in a multipartite system, it has been introduced a new entanglement measure called Localizable Entanglement (LE). It represents the maximal amount of entanglement that can be localized on average in a couple of subsystems by doing local measurements in the rest of the system. Despite of the clearness and usefulness of this multipartite entanglement measure, generally speaking, it is very difficult to evaluate the LE since it requires an optimization over all possible local measurement strategies. In this work we concentrate on a tripartite system in a thermal state succeeding in calculating the exact localizable entanglement as a function of the temperature. The results obtained are usefully integrated with those reached analyzing the behaviour of the concurrence function against the temperature, gaining a deeper insight on the entanglement present in our system.

Experimental realization of programmable quantum gate

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We experimentally demonstrate a programmable single-qubit quantum gate. This device applies a unitary phase shift operation to a data qubit with the value of the phase shift being fully determined by the state of a program qubit. Exact specification of the phase shift would require infinitely many classical bits. This is a striking feature of demonstrated programmable quantum gate because information on phase shift is faithfully encoded into a single quantum bit. The theoretical success probability of the protocol for our experimental realization is 25 %. Our linear optical implementation is based on the encoding of qubits into polarization states of single photons, two-poton interference on a polarizing beam splitter, and measurement on the output program qubit.We characterize the programmable gate by full quantum process tomography. The achieved average quantum process fidelity is 97.1 %. Moreover, using a different set of program states the device can operate as a programmable partial polarization filter with attained fidelity over 97 %.

Non-classical correlations of two interacting qubits coupled to independent reservoirs

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(oral, section D)

The master equation of a system of two coupled qubits is derived taking into account their interaction with two independent bosonic baths. Important features of the dynamics are brought to light, such as the stationary state at general temperatures and the behaviour of the entanglement, which shows the phenomena of sudden death and sudden birth as well as the presence of stationary entanglement for long times [1,2]. The analysis is carried out both at zero and at generic temperatures. The model presented is quite versatile and can be of interest in the study of Josephson junction architectures and of cavity-QED.

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[2] R. Migliore et al., Phys. Status Solidi B 246, 1 (2009).

Generation of hybrid cluster states using non-demolition measurements

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(poster)

It was recently shown that special types of multipartite state, known as cluster states represent a resource for universal one-way computation, an extremely promising type of quantum computing. Information can be written onto these clusters where it is processed and can

then be read out via one-qubit measurements. This idea has been extended to include continuous variables (CV) with the advantage that CV states are simpler to generate and manipulate. Several schemes have been proposed for CV clusters involving four light modes, then more recently four atomic ensembles. Here a scheme is proposed for the generation of a cluster state of two atomic ensembles and two light modes, a so called hybrid cluster state. The quantum variables that correspond to position and momentum are the spin operators of the atoms. In our proposal a light mode, squeezed in the y polarization, is passed through each atomic ensemble with interactions that are governed by QND-type Hamiltonians. These interactions allow the atomic ensembles to pick up information about the light fields. We then introduce 'entangling pulses', which also interact via QND Hamiltonians and so pick up information about both the light and atoms. At the output, the entangling pulses are then measured to infer the spin (polarization) values of the atoms (light) in a non destructive way. This process is repeated on each atomic ensemble individually and on the light emerging from the atoms. The protocol generates the hybrid continuous variable cluster state. The atomic nodes open new possibilities for addressing and manipulating the hybrid cluster, whereas its implementation is simpler than that of the four-atom clusters.

Solid-state quantum memory for photons at telecommunication wavelength

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(oral, section F)

Quantum memories are the building block of quantum repeaters, a scheme which was proposed to extend the distance of quantum communication in fiber networks [1]. The capability of interfacing photons at telecommunication wavelengths that can travel with low loss in optical fibers and quantum memories is interesting in this context (see e.g. [2]). The only proposal to date for a quantum memory for photons at telecom wavelength is based on Erbium doped solids, which have an absorption line at 1536 nm. We present a proof of principle of solid state quantum memory for photons at telecommunication wavelengths. Weak pulses of light at the single photon level are stored for a time up to 600 ns, and retrieved on demand in a $Y2SiO_5$ crystal doped with Erbium ions, cooled at 2.6 K. The memory is based on the Controlled Reversible Inhomogenous Broadening (CRIB) protocol [3]. The idea is to trigger the collective emission of light absorbed by an ensemble of ions by controlling their absorption profile with an external electric field. A single narrow absorption line is first created using spectral holeburning techniques [4]. This line is then artificially broadened by an external electrical quadrupole field, thanks to the linear Stark effect. The line is broadened in a way that spectrally matches the light quanta to be stored. At a time τ after the absorption, the polarity of the field is changed, which induces a rephasing of the atomic dipoles that leads to a collective reemission of the absorbed light at a time 2τ. In the present experiment, only a small fraction of the incident photons (of order of 10^{-3}) are stored and re-emitted, due to the limited absorption in the initial peak and to imperfect optical pumping. In order to be able to detect the retrieved photons, we used a superconducting single photon detector (SSPD) featuring an extremely low dark-count rate ($\sim$ 10 Hz). Difficulties concerning the efficiency of the memory and the sources of noise as well as methods to overcome them will be discussed.

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Separability and entanglement: what symmetries and geometry can say

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(oral, section D)

Entanglement of systems is considered not only an important physical resource but the essential feature for our description of how nature behaves at micro and mesoscopic level. In the 1990s we have witnessed a breakthrough with the establishment of a sound criterion for deciding whether a bipartite system, of low dimension in Hilbert space, is separable or entangled, it is the so-called Peres-Horodecki criterion (PHC), following its discoverers names. This criterion is based on constructing a new matrix by doing a transposition of one of the particles of the joint system state and looking for possible negative eigenvalues that would indicate an entangled state. Thereafter several other criteria have been discovered, as the negativities and concurrences. Several physical explanations were advanced to justify physically the reason for such criteria and their relation to entanglement, however they are still imbued with a component of esoterism. Here we present another insight based on non-unitary symmetries in a R3 space (isomorphic to H2 x H2), that consist in constructing a new matrix, out from the original one, doing a reflection (non-unitary operation), through particular plane, on one polarization vector and on one index of the correlation matrix, both related to one single particle. Then we consider states belonging to the D-7 manifold class and new parameter-dependent variables are introduced. These ingredients allowed us to view the PHC in terms of invariants that transform according the Lorentz non-compact SO(3,1) group. These can be classified as separable-like or entangled-like, since they present a similarity with the time-like and space-like distances of relativity. In the phase space defined by those variables we identify two regions separated by a border, a conical surface. The separable states are points laying within the cone or on its surface, while elsewhere, beyond the cone, the points stand for entangled states. A state is represented by a specific line, which becomes its signature. The line may cross the border, going from one region to the other, as a particular feature some crossings can be recognized as the 'sudden death' phenomenon.

Phase estimation with Gaussian states

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(oral, section C)

In this talk I study the problem of estimating the phase of Gaussian states states within a Bayesian framework. In the first part I consider pure squeezed vacuum states. I derive bounds on the average Holevo variance for an arbitrary number N of uncorrelated copies. It will be shown that it scales with the mean photon number, n, as dictated by the Heisenberg limit, i.e., as n^{-2}, only for $N > 4$. For $N \leq 4$ this fundamental scaling breaks down and it becomes $n^{-N/2}$. I also compute the variance for repeated individual measurements (without classical communication or adaptivity) and find that the standard Heisenberg-limited scaling is recovered for large samples. In the second part I thackle the phase-estimation precision for mixed Gaussian states (displaced thermal and squeezed thermal states) in the single-copy and many-copy regimes. I find the rather suprising result that while for displaced thermal states an increase in temperature reduces the estimation fidelity, for squeezed thermal states a larger temperature can enhance the estimation fidelity. The many-copy optimal bounds are compared with the minimum variance achieved by three important single-shot measurement strategies: Canonical phase, heterodyning and homodyning. I will show that adaptive homodyning schemes do attain the optimal bounds for displaced thermal states, but for squeezed states they yield fidelities that are insensitive to temperature variations and are, therefore, sub-optimal. I apply these results to investigate the influence of losses in an optical metrology experiment

Dynamics of spin systems coupled to bosonic baths beyond the Markov approximation

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(poster)

The dynamics of two spins, interacting or not, embedded in bosonic baths, has gained more and more interest in the last decades both from theoretical and applicative point of view. In particular the attention has been focussed on the entanglement evolution under the hypothesis of weak coupling regime and Markov approximation. In the present work we consider two interacting spins coupled to two independent bosonic baths. Starting from a general initial condition, we solve the dynamics of the system without the markov approximation. Exploiting our result we analyze the entanglement evolution in the two spins considering different spectral densities of the baths.

Better-than-Heisenberg scaling of sensitivity in metrology

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Quantum correlated probes (such as squeezed or entangled states) have been demonstrated to be useful for improving the sensitivity of a broad class of measurements (interferometry, magnetometry, imaging, etc.) with the uncertainty that scales with a law known as Heisenberg limit. Dynamics in which probes are coupled non-linearly to the

parameter being estimated can beat such limit without any use of entanglement. In a polarization-based atom-light interface, a Hamiltonian that is non-linear in the Stokes operators can be produced using optical non-linearities: here we investigate application to precision measurements with better-than-Heisenberg scaling. For reference, we consider an atom-light interface consisting of pulses of polarized light interacting with an ensemble of 1Mio cold 87Rb in dipole trap, the atomic state is probed via measurements of polarization changes in the light. In linear regimes such changes are independent of the number of photons used. We investigated various possible scenarios in which on the contrary polarization changes do depend on the number of photons. An effective Hamiltonian is derived via adiabatic elimination and operator dynamics is computed, at the same time using the Maxwell-Bloch equations and a self-homodyne model of pulsed polarimetry, we calculate the effective non-linear polarizability of atoms and the resulting polarization rotation. The signal-to-noise scalings are compared for the cases of linear and non-linear interaction including the noise performance of a real detection system. To see the different scaling due to non-linear polarizability effects, the simulations indicate that experimental requirements appear to be achievable with the present quantum interface system.

Experimental three-color continuous-variable entanglement

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(oral, section B)

Entanglement between continuous-variable (CV) systems has been increasingly investigated in recent years. Of particular interest is the generation of higher orders of entanglement for future quantum communication networks. We demonstrate here, for the first time, the direct generation of CV entanglement between more than two subsystems. Squeezing in different combinations of three field quadratures is essential for the demonstration of entanglement. In a triply resonant optical parametric oscillator (OPO) operating above threshold, pump, signal, and idler become entangled. In contrast with tripartite entanglement produced by three squeezers and linear optics, here all three fields have different wavelengths (colors): 532 nm, 1,063 nm, and 1,065 nm. The entanglement is demonstrated using the criteria by van Loock and Furusawa (directly linked to the squeezing mentioned above) as well as the positivity under partial transposition (PPT), which is necessary and sufficient for gaussian states. Our states are indeed gaussian, within the experimental resolution. We also test a criterium for 'genuine' multipartite entanglement (by Hyllus and Eisert), with positive results. A crucial step to achieve entanglement was to cool the nonlinear crystal and reduce phonon noise which has hindered our previous attempts. Nevertheless, this extra noise still gives rise to nontrivial entanglement dynamics of the generated state. In our CV system, we experimentally observe disentanglement of one of the fields for finite losses, in a situation akin to the so-called 'entanglement sudden death'. Multicolor entanglement, as experimentally generated here, opens the way to quantum networks with different pieces of hardware in each node, interacting resonantly with light at different frequencies.

Bayesian noisy phase estimation in qubit systems: from theory to experiment

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(oral, section C)

We address Bayesian estimation of an unknown phase shift imposed to a qubit when non-dissipative phase noise affect the propagation.

The comparison with the ultimate quantum limits to precision, taking into account the biased nature of the Bayes estimator in the non-asymptotic regime, is given. The stability of the method and the achievement of the Bayes estimator asymptotic optimality is also analyzed in some details. Experimental demonstration of our scheme relates on a setup based on a programmable liquid crystal phase modulator that allows both to manipulate the optical qubit polarization and to simulate the noise affecting propagation.

Quantum interference of a biphoton at a blazed grating

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(oral, section D)

Correlations between photons are interesting for a number of applications and concepts in metrology in particular for resolution improvements in different methods of quantum imaging. Since Fock-states of N-photons of wavelength λ in interference schemes acquire N-times the phase shift of single photons these states can appear as if they had a de Broglie wavelength of λ/N. This has been studied for diffraction at ordinary gratings in [1]. Furthermore using a blazed grating different number states could be separated or sorted on the one hand. On the other hand evaluation of the diffraction pattern by the one-photon and two-photon rate allows for an analysis of the spatial correlation between photons. An experimental demonstration of these ideas tested for a biphoton beam is presented in this paper. Correlated photon pairs at 780 nm are generated by parametric down conversion (PDC) in a beta-barium-borate crystal pumped by picosecond pulses at a wavelength of 390 nm with an average power of 40 mW. Utilizing a Hong-Ou-Mandel (HOM) interference a biphoton beam is generated. This biphoton beam has been used to illuminate a blazed grating with a grating period of 25 μm. The two-photon rate diffraction distribution shows an order of diffraction expected for half the original wavelength at 390 nm. Our measured diffraction distributions results are in good agreement with the theoretically expected distributions. Consequently such a diffraction at a blazed grating has perspectives for the characterization of the spatial correlation of biphotons and the purifaction of a biphoton beam of a certain correlation strength.

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Spatial entanglement analysis of biphotons

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(oral, section D)

Correlations in light can be used for a variety of applications in metrology and quantum imaging, where several schemes rely on multiphoton absorption. Thus, a detailed knowledge of the temporal and spatial correlations between photons is desired. We characterize here the quantum correlations of photon pairs generated by type II parametric down-conversion, in an experiment similar to Refs. [1,2]. Our goal is the complete mapping of the correlations in position and momentum transverse to a biphoton beam. The biphoton source is a 2 mm thick beta-barium-borate crystal pumped with mode-locked ps pulses (390 nm, 40 mW, beam diameter of 160 μm). We have separate control over the spatial modes of the photon pairs, incombination with a Hong-Ou-Mandel interferometer. To measure the correlation in (transverse) position and the anti-correlation in momentum, we use a Hanbury-Brown-Twiss setup with two single-mode fiber probes, one in each path behind a beam splitter. The fibers have a mode-field diameterof 5 μm. The near field or far field of the biphoton source is imaged onto two transverse planes where the fibers can be moved independently over 20 μm x 20 μm and measure coincidences.

We find that the joint detection probability in position or momentum space is well described by a bivariate normal distribution. We thus obtain from the coincidence data two covariance matrices. Their diagonalization gives a variance product below the classical bound: $\Delta(x_1 - x_2)^2 \Delta(p_1 + p_2)^2 = (0.16 \pm 0.05)\hbar^2$. According to Ref. [3], this proves the spatial entanglement of the biphotons.

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Experimental proof of commutation rules by superpositions of quantum operators

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(poster)

We directly prove the commutation relation between bosonic creation and annihilation operators by realizing an appropriate coherent superposition of sequences of single-photon additions and subtractions. The basic quantum operators were separately implemented in recent works and separate sequences of the two have recently allowed the direct experimental verification of the non-commutativity of the creation and annihilation operators. Here we present the experimental realization of a scheme for the arbitrary superposition of quantum operators and apply it to directly and completely prove the commutation relation. Besides its importance in the study of the foundations of quantum mechanics, the experimental access to arbitrary superpositions of quantum operators is of high interest for generating and manipulating quantum states for emerging technologies.

Events and probabilities in quantum theories

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(oral, section G)

In Quantum Theories at every event is associated a closed subspace (H, K, ...) of some separable Hilbert space, to elementary (not refinable) events correspond uni-dimensional subspaces – or normalized vectors. If the elementary event E is certain at (proper) time t=0, P(H, t, E) is the conditional probability of event H at time t>0, in standard theories P(H, t, E) = Trace(H(t).E), where the subspaces are identified with the corresponding orthogonal projectors. For two (or more) events H and K, at time t>s>0, P(H, t, K, s, E) is their joint probability, conditioned by E, now the rules of probability calculus lead to the reduction formula for the intermediate event, that is P(H, t, K, s, E) = Trace(H(t).K(s).E.K(s).H(t)). Obviously this 'reduction' has nothing to do with observations or measurements, the only thing that happens is event K, at time s. And, in general, there are not external, classical observers: all the above is valid for every object (a particle, a cat, a philosopher). If, for example, K and K* are two ortho-complementary subspaces (which represent a spin up or down particle, a dead or alive philosopher) then, for t>0, can happens that both P(K, t, E) > 0 and P(K*, t, E) > 0, we can say, figuratively, that there is a 'superposition', with respect to K and K*. In Classical Theories at every event is associated a subset (A, B, ...) of some reference set X, to elementary events correspond one-element subsets – or point of X. If the elementary event represented by the point x is certain at (proper) time t=0, P(A, t, x) is =1 if x(t) belong to A, otherwise is =0, we can speak of 'determinism', but, obviously, this classical description is only a rough approximation of what happens in Nature.

Recent developments in the study of higher-order non-classical states

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(poster)

Our recent observations on higher order nonclassicality is reported. It is shown that a generalized notion of higher order nonclassiclaity (in terms of higher order moments) can be introduced. Under this generalised framework of higher order nonclassicality, conditions of higher order squeezing (HOS)and higher order subpoissonian photon statistics (HOSPS) are derived. Further, with the help of simple density matrices, it is shown that the higher order antibunching (HOA) and higher order subpoissonian photon statistics (HOSPS) are not the manifestation of the same phenomenon and consequently it is incorrect to use the condition of HOA as a test of HOSPS. It is shown that the HOA and HOSPS may exist even in absence of the corresponding lower order phenomenon. It is also shown that the potential sources of single photon must satisfy the condition of HOA. Most of the intermediate states are shown to satisfy the criteria of HOA and a comparison between these potential single photon sources is reported here.

Photon-number statistics of twin beams and their non-classical properties

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Joint signal-idler photoelectron distributions of twin beams have been measured recently in two different regimes: either the mean number of photon pairs per one pump pulse is considerably lower that the number of independent modes [1] or vice versa [2]. Using the model of superposition of signal and noise we characterize properties of experimetal twin beams in terms of quasi-distributions [3]. Joint signal-idler photon-number distributions are also reconstructed using the method of maximum likelihood. Negative values as well as oscillating behaviour in quantum region are characteristic for the determined joint signal-idler quasi-distributions of integrated intensities. The larger the mean number of photon pairs per mode the weaker the quantum features are. However, they exist even in the mesoscopic regime, i.e. when tens of photon pairs per mode occur on average. Also conditional and difference photon-number distributions have been found to be sub-Poissonian and sub-shot-noise, respectively. Violation of classical inequalities for photocount as well as photon-number distributions has been observed. Criteria of non-classicality of twin beams have been discussed. Also statistical properties of three mesoscopic correlated fields generated in two inter-linked parametric processes have been investigated.

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Nonlinear layered media as promising sources of entangled photon pairs

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A vectorial quantum model of spontaneous parametric down-conversion in nonlinear layered media pumped by both cw and pulsed lasers has been developed [1,2]. Relation between transmissivity of a nonlinear structure and ability to generate efficiently entangled photon pairs has been elucidated. Several structures operating in visible spectral range and composed of up to several tens of layers have been suggested using GaN/AlN. Their spectral and temporal properties as well as characteristics in the transverse plane of the down-converted fields (intensity profile, correlation area) have been studied in detail. It has been shown that also the effect of surface spontaneous parametric down-conversion occurring at the boundaries between linear and nonlinear layers can give appreciable contribution to photon-pair generation rate. If positions of boundaries are random, photon pairs with extremely narrow intensity spectra can be emitted. Under special conditions, entangled photon pairs anti-symmetric in frequencies of the signal and idler fields can be generated [3]. Temporal anti-bunching and anti-coalescence on a beam splitter are their typical properties. Having this in mind nonlinear layered media can be considered as promising sources of photon pairs for future metrology as well as quantum-information applications.

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Quantitative wave-particle duality and sensitivity of phase measurement

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(poster)

In an atom interferometry, the atom behaves similarly as a classical particle. In the analysis quantum mechanical particles including atoms atre considered in general. An interferometric scheme has been developed in [1], in which the information on the path chosen by the quantum mechanical particle is stored in the state of this particle.The analysis takes into account a nonstandard dependence of the path distinguishability on the length difference and is more complicated than the standard one. In the standard case, a dynamical approach has been developed in [2]. Unitary operators have been utilized, which are used in the study of the optical interferometry with nonclassical states. We apply the dynamical approach also in the case where the path distinguishability depends on the length difference. While the read-out of the which-path information behind the second beam splitter is assumed in [1], we consider such a process also in front of the second beam splitter. We expand on derivations of inequalities according to [1], i. e., with their measure of sensitivity. We include the variance of a directly measured quantity in the sensitivity measure in the standard and modified schemes.

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Geometric representation and quantum entanglement in multiple-qubit systems

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(poster)

This investigation is focused on a geometrical explanation of entanglement between qubits using Hopf fibrations as a helpful mathematical tool for the reduction of the Hilbert space of the composed system. Basically, a Hopf fibration is a map from a higher dimensional unit sphere to a lower dimensional unit sphere which is not null-homotopic. The simplest example of a Hopf fibration is the map from a three-sphere into a two-sphere in three dimensional Euclidean space, which helps to define the well known Bloch sphere as a representation of one pure qubit. Using this first Hopf fibration all the states differing by a global phase are identified with a unique point in the two-sphere. The second Hopf fibration is used for the geometrical explanation of the system of two qubits, this fibration maps a seven-sphere to a four-sphere; the fibre is now a three-sphere and the base is a four-sphere, this means that all the states differing by a unit quaternion are mapped onto the same value in the base. This fibration is entanglement sensitive because in the separable case, the original Hilbert space is reduced to a product of two Bloch spheres. The next step in this iteration is the quantum system of three qubits in which case the third Hopf fibration is useful. In the generic case this Hopf fibration maps an eight-sphere that defines the base, nevertheless when the system is bi-separable the fibration maps once more into the subspace of a two-sphere. This interesting result means that when bi-separable conditions are satisfied then the base is again a Bloch sphere corresponding to the unentangled qubit. When the system of three qubits is not separable, it is possible to define an entanglement measure using the coordinates of the base that has the information about the correlation between qubits; this measure is related with the 'tangles'. The two-tangle measure is identical to the entanglement measure defined from the third Hopf fibration and it is independent of the chosen separated qubit; obviously the entanglement degree for the GHZ and W states coincide in that the entanglement is not null in both cases but with the difference that GHZ is the maximally entangled state. An important point is that the entanglement measures defined with the Hopf maps match exactly with know and well defined entanglement measures as concurrence and tangles in two and three qubits respectively; this worthy relationship give an important hint of the possibility of an extension of this geometric analysis for four qubits.

Experimental work on entangled photon holes

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(oral, section D)

In addition to its fundamental importance, entanglement has recently been identified as a key resource for quantum information processing. Consequently, there has been a renewed interest in developing new forms of entanglement and their possible applications. In this talk, I will review our group's recent experimental work on generating a new form of optical entanglement called 'entangled photon holes' (EPH's). In contrast to entangled states based on polarization, momentum, or some other physical property of photon pairs, the entanglement here is due to the absence of the photon pairs themselves. Under the right conditions, these correlated absences in otherwise constant background beams can lead to nonlocal effects similar to those seen with entangled photon pairs. In principle, EPH states can be generated through strong two-photon absorption, which selectively removes a single photon from two independent weak coherent states. We have recently been investigating an alternative approach in which weak coherent states are mixed with parametric down-conversion (PDC) sources in interferometers, and quantum interference effects are used to suppress the probability that single photons are simultaneously emitted into two output ports. The interference effects rely on the indistinguishability of the various sources which, in our experiments, is accomplished by using pulsed PDC techniques. The timing of the pulses can be arranged to produce time-bin-like EPH's, in loose analogy with the time-bin entangled photon pairs pioneered by Gisin's group. By sending these states to distant interferometers, it may be possible to violate Bell's inequality with entangled photon holes.

Quantum information science with photons on a chip

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(oral, section D, **invited** *)*

We have developed an integrated waveguide approach to photonic quantum circuits [1]. We demonstrate high-fidelity silica-on-silicon integrated optical realizations of key quantum photonic circuits, including two-photon quantum interference with a visibility of 94.8(5)%; a controlled-NOT gate with an average logical basis fidelity of 93.3(2)%; and a path entangled state of two photons, relevant toquantum metrology, with fidelity >92%. We use these devices to demonstrate multi-photon effects relevant to quantum metrology [2],quantum information processing [3], and quantum measurement [4]. The monolithic nature of these devices means that the correct phase can be stably realized in what would otherwise be an unstable interferometer, greatly simplifying the task of implementing sophisticated photonic quantum circuits. We fabricated 100's of devices on a single wafer and find that performance across the devices is robust, repeatable and well understood.

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Quantum memory for light

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(oral, section E, **invited** *)*

Quantum memories for light are crutial components of quantum information networks. Quantum memory can be viewed as a channel for a transfer of quantum states from photons to atoms. Of particular importance are the channels which can outperform any possible classical channel. The classical channel performance can be characterized by its benchmark maximal fidelity which until recently has been known only for few classes of states including qubits [1] and coherent states [2]. Quantum channels such as teleportation and quantum memory for light demonstrating fidelities higher than classical benchmarks have been reported for coherent states [3] and for qubits [4]. Recently the classical benchmark fidelity has been found for a new class of states: displaced squeezed states [5]. I will describe an experiment [6] presenting a quantum channel which outperforms any classical memory for this new class of states which play fundamental role in quantum mechanics. The experiment utilizes room temperature spin-polarized alkali vapor held in two glass cells with spin-preserving coating which has proven to be an outstanding memory unit, as demonstrated in earlier experiments [3B,3C]. A squeezed state of light generated by an optical parametric amplifier is displaced and transferred over a distance of several meters to the atomic memory where it is stored for about a millisecond. The memory mechanism is based on a combination of the Raman interaction with a homodyne quantum measurement and feedback. The achieved quantum channel fidelity of 0.62 ± 0.02 for squeezed states with 6.1dB of squeezing and an arbitrary phase, displaced within a square with dimensions ±4 in vacuum units, is above the classical benchmark fidelity of 0.50 calculated using the method of [5]. Besides its fundamental importance the new quantum channel paradigm can be used for encoding and transmission of quantum information in protocols which use squeezed and Einstein-Podolsky-Rosen entangled states.

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Characterization of bipartite states: From theory to experiment

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(oral, section B)

Bipartite light beams endowed with nonclassical correlations are crucial resources for quantum technology and represent a building block for the development of an integrated quantum network. Their full characterization has a fundamental interest in its own and represents a tool for the design of protocols of quantum information processing in realistic conditions. Remarkably, entangled states produced by optical parametric oscillator sources are Gaussian states and thus may be fully characterized by the first two statistical moments of the field modes. In turn, the covariance matrix contains the complete information about entanglement of Gaussian states, i.e., about their performances as a resource for quantum technology. We present the full experimental reconstruction of Gaussian entangled states generated by a type-II optical parametric oscillator below threshold. Our scheme provides the entire covariance matrix using a single homodyne detector and allows for the complete characterization of bipartite Gaussian states, including the evaluation of purity, entanglement, and nonclassical photon correlations, without a priori assumptions on the state under investigation [1,2].

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[2] V. D'Auria, S. Fornaro, A. Porzio, S. Solimeno, S. Olivares and M. G. A. Paris, Phys. Rev. Lett. 102, 020502 (2009).

Rubidium resonant squeezed light from a diode-pumped optical-parametric oscillator

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(poster)

Phase-sensitive amplification in an optical parametric oscillator is a proven technique for generation of squeezed states of light. Commonly, low-noise titanium sapphire lasers are used to pump the oscillator. The use of diode lasers for this purpose would allow squeezing at wavelength unreachable with titanium sapphire lasers. Furthermore, diode lasers are low cost and robust. However, their excess phase noise would be an obstacle for the production of phase-sensitive quadrature squeezed states. We present the results of quadrature and polarization squeezing generated by a sub-threshold optical parametric oscillator resonant to rubidium D1 line and pumped by a frequency-doubled diode laser [1]. We show a technique to eliminate the effects of laser phase noise on quadrature squeezing. This technique uses cavity stabilization of the laser frequency, in combination with a carefully chosen delay between the squeezed light and the local oscillator beam. By introducing fiber delay lines into the local oscillator path this delay can be matched so that phase fluctuations are canceled out in white-light configuration. For the theoretical description of this effect we adapted the squeezing theory of Collet and Gardiner [2] including phase noise of the pump laser. This investigation confirms that the balancing of the squeezed light path-length with the local oscillator allows the measurement of squeezing. The obtained squeezing results can be used for optimal phase analysis [3]. Being resonant to atomic transition our squeezed light can also be used for optimal estimation of atomic spin states of rubidium.

[1] A. Predojević, et al., Phys. Rev. A 78, 063820 (2008).
[2] M. J. Collett and C. W. Gardiner, Phys. Rev. A 30,1386 (1984).
[3] A. Monras, Phys. Rev. A 78, 033821 (2006).

Noiseless linear amplification

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(oral, section A)

We introduce the concept of non-deterministic noiseless linear amplification. That is we show that it is possible to non-deterministically implement the transformation $|a\rangle \rightarrow |ga\rangle$, where $|a\rangle$ is a coherent state of amplitude a and g is a real number greater than 1. We propose a linear optical realization of this transformation that could be built with current technology. We discuss two applications, ideal probabilistic cloning of coherent states and distillation of continuous variable entanglement. For the latter example we demonstrate that highly pure entanglement can be distilled from transmission over a lossy channel. We will also present progress towards an experimental demonstration of noiseless linear amplification.

Scattering-quantum-walk searches on highly symmetric graphs

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(oral, section F)

Grover search for an element within an unstructured database has showed up to be one of few important quantum algorithms where a speedup over classical algorithms is possible. The algorithm has been extensively studied and led to its several generalizations and variations. In the topic of quantum walks Shenvi, Kempe and Whaley showed, that a quantum walk on a hypercube having the same coin for all vertices except one — the target vertex — behaves very

similarly as the Grover search. Here we show that the basic element of Grover search — quantum oracle — can be implemented in quantum walks and in this way we separate the quantum walk on different kinds of graph from the search problem. Utilizing scattering quantum walk formalism we are able to solve many such searches on highly symmetric graphs, where the large automorphism group of these graphs leads to a significant simplification of the problem and the evolution takes place in a Hilbert space of small dimension, not unlike in the standard Grover search.

Quantum optics with ultracold molecules

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(oral, section E, **invited** *)*

A plethora of quantum optical phenomena like the generation of squeezed light occur in open systems where the loss of photons is an essential part of the system dynamics. This is strikingly different for matter waves where the number of particles in the system is usually conserved, or more precisely, the loss of particles is unwanted for most applications. However, recent experiments with ultracold molecules in optical lattices [1] have changed this situation by implementing concepts of dissipative quantum optics in matter-wave systems. The talk introduces the main features of such experiments and highlights some remarkable phenomena like the inhibition of matter-wave tunnelling by observation (Zeno effect) and the generation of a highly correlated quantum gas by means of dissipation, with atom antibunching better than 1:2000 [2].

[1] T. Volz et al., Nature Physics 2, 692 (2006).
[2] N. Syassen et al., Science 320, 1329 (2008).

Postselection as a tool in quantum information

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(oral, section F, **invited** *)*

In order to prove security of a quantum cryptographic scheme, one needs to take into account all possible attack strategies an adversary may choose. This is generally very demanding because the number of different strategies is huge. A similar difficulty also arises in the context of other information-theoretic problems, e.g., the analysis of interactive arguments.
In this talk, I present a method, called postselection technique, which can be used to simplify such proofs. When applied to quantum key distribution, it reduces the number of different attacks to be considered to one. In other words, general security of a protocol follows from its security against one particular 'universal' attack.

Quantum simulation in ion traps and BECs

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(oral, section E, **invited** *)*

Two proposals for quantum simulations in Ion traps and BECs will be described. It will be shown that the radial degree of freedom of strings of trapped ions in the quantum regime may be prepared and controlled accurately through the variation of the external trapping potential while at the same time its properties are measurable with high spatial and temporal resolution. This provides a new testbed giving access to static and dynamical properties of the physics of quantum-many-body systems and quantum phase transitions that are hard to simulate on classical computers. Furthermore, it allows for the creation of double well potentials with experimentally accessible tunnelling rates and with applications in testing the foundations of quantum physics and precision sensing. A scheme for the study of methods for detecting Unruh-like acceleration radiation effects in a Bose-Einstein condensate in a 1+1 dimensional setup will be described. In particular, the dispersive effects of the Bogoliubov spectrum on the ideal case of exact thermalization will be explained.

Full quantum tomography of twisted photons

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(oral, section D)

We propose a complete tomographic reconstruction of photons carrying orbital angular momentum along their propagation direction. For certain states, the tomographical measurement reduces to the determination of the angular probability distribution at different times of free evolution. The experiments are currently being run in the lab [1]. To represent the quantum state we introduce a bona fide Wigner function defined on the discrete cylinder, which is the natural phase space for the pair angle-angular momentum. This Wigner function appears to resemble remarkable similarities to the discrete Wigner function, while being rather different from the Wigner function of the Heisenberg-Weyl group [2].

[1] I. Rigas, L. L. Sánchez-Soto, A. B. Klimov, J. Řeháček and Z. Hradil, Phys. Rev. A 78, 060101 (R) (2008).
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Squeezed entangled state generated by a Dicke phase-transition

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(poster)

We study how the entanglement between two modes of the electromagnetic field can be created by a Dicke phase transition. We find that bipartite mode state becomes a squeezed entangle state in the quantum phase transition by considering A atoms interacting dispersively with the two cavity modes.

Transfer of the internal atomic states between two trapped ions and its dependence on the vibrational phonons

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(poster)

In this communication we present a study of a system made up of by two two-level ions (atomic frequency ω_a) inside different cavities, with the same frequency ω and atom-field coupling constant g. The cavities are connected by an optical fiber, and each ion is trapped inside a harmonic potential with movement frequency ν. In this case the trap center is located in the cavity field node. Here we have considered the 'short fiber limit', where only a single mode of the fiber interacts with the cavity fields (with coupling constant λ). Our results were obtained using the Rotating Wave Approximation under following three conditions: (i) $\omega, \omega_a >> \sqrt{2}\lambda, 3\nu$, (ii) $\lambda, \nu >> g$ and (iii) $\sqrt{2}\lambda - 3\nu >> g$. It was also convenient to define the function $\beta(k) = 1-(1+2k)\,\eta^2/2$ (where η is the Lamb-Dicke constant). In the carrier band ($\omega_a - \omega = 0$) at each specific time $t_n = (2n+1)\pi/\beta(k)g$

$(n = 0, 1, 2, ...)$, the quantum state transfer of superposition states from the internal state ions 1 to 2 was observed. In other words, at this time the state of the system undergoes the following transition:

$$\begin{aligned} &\left[\cos\theta \left|g\right\rangle_1 + e^{i\phi}\sin\theta \left|e\right\rangle_1\right] \left|k\right\rangle_{a1} \left|0\right\rangle_{b1} \left|0\right\rangle_c \left|0\right\rangle_{b2} \left|g\right\rangle_2 \left|k\right\rangle_{a2} \\ \rightarrow &\left|g\right\rangle_1 \left|k\right\rangle_{a1} \left|0\right\rangle_{b1} \left|0\right\rangle_c \left|0\right\rangle_{b2} \left[\cos\theta \left|g\right\rangle_2 + e^{i(\varphi-\mu_n)}\sin\theta \left|e\right\rangle_2\right] \left|k\right\rangle_{a2} . \end{aligned} \tag{1}$$

For initial state we considered that the vibrational modes $\hat{a}_1$ and $\hat{a}_2$ of the ions are in the Fock state (with the same number of phonons k), while the cavity modes $\hat{b}_1$, $\hat{b}_2$, $\hat{c}$ and the fiber mode are in their respective vacuum states. We can see in (1) that there is a difference $\mu_n = (2n+1)\frac{\omega}{\beta(k)g}\pi$ in the relative phase that can be corrected by one-qubit operations on the second ion. We obtained exactly the same state for the ion 2 when the condition $\frac{\omega}{\beta(k)g} = 2l$ $(l = 1, 2, 3, ...)$ is satisfied. We also noted that the motional state of the ion affects the efficiency of the transmission, producing a delay time dependent on the phonons number.

Minimal energy cost for quantum information processing: measurement and information erasure

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(poster)

In 1867, J. C. Maxwell proposed 'Maxwell's demon', which has the capability to perform information processing at a microscopic level. Since then, numerous studies have been conducted on the relationship between information processing and thermodynamics [1]. For example, according to the 'Landauer's principle', in erasing one bit of information from the memory of the demon, at least k_BTln2 of heat should be dissipated into the environment with the same amount of work being performed on the memory. However, the proof of the Landauer's principle in terms of statistical mechanics [1] is valid only for memories which have a kind of symmetry. In the present work [2], we have derived the fundamental lower bounds of the thermodynamic energy cost needed for measurement and information erasure, by incorporating the recently developed techniques of quantum information and measurement into nonequilibrium quantum statistical mechanics. The lower bound for the erasure vindicates the 'Landauer's principle' for a special case, but otherwise implies its breakdown without any contradiction to the second law of thermodynamics. We have also derived the fundamental upper bound of the work that can be extracted by the demon. Our results constitute the second law of 'information thermodynamics', in which the information content (i.e., the Shannon information and the mutual information) and thermodynamic variables (i.e., work, heat, and the free energy) are treated on an equal footing.

[1] H. S. Leff and A. F. Rex, (eds.), *Maxwell's demon 2: Entropy, Classical and Quantum Information, Computing* (Princeton University Press, New Jersey, 2003).
[2] T. Sagawa and M. Ueda, Phys. Rev. Lett. 100, 080403 (2008); arXiv:0809.4098 (2008).

Simultaneous generation and frequency up-conversion of entangled optical images

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(poster)

Entangled optical images are generated in conventional parametric three-wave processes at high frequency pumping. When a coherent signal at frequency ω_1 and an intense pumping wave at frequency ω_p irradiate a crystal with second order nonlinearity at the output of the crystal an extra image at frequency $\omega_2 = \omega_p - \omega_1$ is formed. These images (at frequencies ω_1 and ω_2) is entangled [1]. We will discuss a coupled nonlinear parametric process which comprises one parametric down-conversion process and two up-conversion ones, so that the wave frequencies obey the following relations: $\omega_p = \omega_1 + \omega_2$, $\omega_1 + \omega_p = \omega_3$, $\omega_2 + \omega_p = \omega_4$. Earlier we studied these interactions in the plane wave assumption [2, 3]. It has been established that the four-wave field, forming in these processes, consists of two pairs of entangled states. In present work these processes are generalized on the case of images parametric amplification and up-conversion. Thus, the nonlinear optical equations are solved in the quasi-optical assumption. For each of the interacting waves the self-transformation and mutual transformation coefficients have been calculated. Also the other characteristics such as signal-to-noise ratio, mean photon number and dispersion of photon number at different frequencies, have been investigated. The possible scheme for teleportation of two-mode entangled images is considered.

[1] *Quantum imaging*, Ed. M. I. Kolobov, Springer Verlag (2006).
[2] A. S. Chirkin, M. Yu. Saigin and I.V. Shutov, *Parametric amplification at low-frequency pumping and generation of four-mode entangled states*, J. Russian Laser Research 29, 336 (2008).
[3] A. S.Chirkin and M. Yu. Saigin, *Four-mode entangled states in coupled nonlinear optical processes and teleportation of two-mode entangled CV states*, Physica Scripta, T134 (2009).

Towards Einstein-Podolsky-Rosen quantum channel multiplexing

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(oral, section B)

A single broadband squeezed field constitutes a quantum communication resource that is sufficient for the realization of a large number N of quantum channels based on distributed Einstein-Podolsky-Rosen (EPR) entangled states. Each channel can serve as a resource for, e.g. independent quantum key distribution or teleportation protocols. N-fold channel multiplexing can be realized by accessing 2N squeezed modes at different Fourier frequencies. We report on the experimental implementation of the N = 1 case through the interference of two squeezed modes and demonstrate all required multiplexing techniques. A multiplication of solely the classical resources of our experiment will allow the establishment of a linearly increasing number of EPR quantum channels between pairs of distant parties.

Wigner functions and path integrals

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(oral, section A)

The Wigner function W(q, p) is a widely used representation of a density matrix as a (not necessarily positive) distribution in phase space. We will demonstrate how its sign oscillations may be interpreted as 'interference fringes' of paths in a path integral. A method of calculation of Wigner functions by means of coherent-state path integration has been proposed [1], this provides an interpretation of its sign oscillations in terms of the area enclosed by the dominant paths. We apply the method to ground states of anharmonic potentials such as the Morse potential and the double well and show how excited states may also be investigated. While the dominant path in a harmonic potential encloses no area, leading (as expected) to a positive Wigner function for a Gaussian state, low-action paths in anharmonic potentials may enclose non-zero area, leading to sign oscillations of the Wigner function. Numerical minimisation of the action [2] indicates that the dominant path does not enclose sufficient area to re-create the sign oscillations of the Wigner function in the ground state if fluctuations are not included. We show how the method can reproduce sign oscillations in the Wigner function for excited states.

[1] J. H. Samson, J. Phys. A: Math. Gen. 36, 10637 (2003).
[2] N. Lindsey, *PhD thesis*, Loughborough University, 2009.

Quanta in a black-box

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(oral, section G, **invited** *)*

In this talk, I shall describe how one can assess the presence of genuine quantum entanglement in a black-box scenario, i.e. without any knowledge about either the physical system under study or the measurements that are being performed. This approach may lead to define 'quality standards' for quantum devices.

Classical capacity of a bosonic memory channel with Gauss-Markov noise

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We present the explicit solution for the classical capacity of an energy constrained bosonic memory channel with a Gauss-Markov process as a noise model. We show that the optimal input power distribution follows a quantum analog to the classical water filling. Furthermore, we conclude that the optimal transmission rate can only be achieved by introducing a finite degree of entanglement between the input states. Finally, in the classical limit we recover the solution of the classical Gaussian channel.

Quantum manipulation of orbital angular momentum photonic states by coherent coupling with polarization

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(oral, section D)

The orbital angular momentum of photons, being defined in an infinitely dimensional discrete Hilbert space, offers a promising resource for high-dimensional quantum information protocols in quantum optics. Here, we introduce and test experimentally a series of optical schemes for the coherent transfer of quantum information from the polarization to the orbital angular momentum of single photons and vice versa [1]. All our schemes exploit a newly developed optical device, the so-called 'q-plate', a suitably patterned non-uniform birefringent plate, which enables the manipulation of the photon orbital angular momentum driven by the polarization degree of freedom [2]. By stacking several q-plates in a suitable sequence, one can also access to higher-order angular momentum subspaces. Our experiments prove that these schemes are reliable, efficient and have a high fidelity. The optical 'spin-orbit' coupling occurring in the'q-plate' also allows entangling the polarization of a single photon with its orbital angular momentum (OAM) [3]. Moreover, we show that two-photon quantum correlations such as those resulting from coalescence interference, in the Hong-Ou-Mandel effect, can be successfully transferred into the OAM degree of freedom [3]. Finally we discuss the generation of hyper-entangled states of polarization and orbital angular momentum and their applications for quantum information processing and for non-locality tests.

[1] L. Marrucci, et al., Phys. Rev. Lett. 96, 163905 (2006).
[2] E. Nagali, F. Sciarrino, F. De Martini, B. Piccirillo, E. Karimi, L.

Marrucci and E. Santamato, arXiv:0902.0740.
[3] E. Nagali, F. Sciarrino, F. De Martini, L. Marrucci, B. Piccirillo, E. Karimi and E. Santamato, arXiv:0810.2417.

Experimental implementation of the Quantum Private Queries with linear optics

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(poster)

The Quantum Private Query is a quantum cryptographic protocol to recover information from a database, preserving both user and data privacy: the user can test whether someone has retained information on which query was asked, and the database provider can bound the quantity of information released [1]. Here we propose a linear optical implementation which exploits the different degrees of freedom of a single photon: it employs the photon's momentum (or time slot) as address qubits and its polarization as bus qubit [2]. In contrast to the original proposal [1], it does not require a quantum random access memory (qRAM) [3] and can be implemented with current technology, but it has sub-optimal communication complexity. The qRAM's absence implies that the binary-to-unary translation to route Alice's query to the appropriate database memory element must be performed by Alice herself. Thus Alice and Bob must be connected by a number of communication channels (spatial optical modes in our implementation) equal to the number N of database elements. A proof-of-principle experimental realization is implemented using only linear optical elements and postprocessing measurements. Its practical feasibility relies on the possibility of using sufficiently fast optical switches to achieve a sustainable communication rate.

[1] V.Giovannetti, S. Lloyd and L. Maccone, Phys. Rev. Lett. 100, 230502 (2008).
[2] F. De Martini, V. Giovannetti, S. Lloyd, L. Maccone, E. Nagali, L. Sansoni and F. Sciarrino, arXiv:0902.0222.
[3] V.Giovannetti, S. Lloyd and L. Maccone, Phys. Rev. Lett. 100, 160501 (2008).

Propagation of quantum light through the turbulent atmosphere

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(oral, section A)

Implementations of quantum cryptography in atmospheric channels between Earth-based stations and between satellites and Earth-based stations require a special knowledge about the propagation of quantum light through turbulent media. In this contribution we propose to consider the atmosphere as a linear attenuating system with a fluctuating transmission coefficient. In the context of such an approach, the probability distribution of the transmission coefficient is the main characteristics of turbulence properties of the atmosphere. We show that this function can be measured by homodyne detection. Moreover, we demonstrate that nonclassical properties of quantum light, such as a sub-Poissonian photocounting statistics, or more generally, the non-positivity of the Glauber-Sudarshan P function, are more robust for weak rather than intense light fields.

Weak values with decoherence

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(oral, section G)

What is an observable? According to von Neumann, the observable is defined as the self-adjoint operator. Is there another representation of the measurement outcome? The answer may be the weak values. The weak value of an observable is experimentally accessible by weak measurements as theoretically analyzed by Aharonov et al. and recently experimentally demonstrated. Furthermore, the weak values help reconsidering the Born probabilistic interpretation. The aim of our work is to construct the quantum measurement for the weak values. We introduce a weak operator associated with the weak values and give a general framework of quantum operations to the weak operator in parallel with the Kraus representation of the completely positive map for the density operator. The decoherence effect is also investigated in terms of the weak measurement by a shift of a probe wave function of continuous variable. As an application, we demonstrate how the geometric phase is affected by the bit flip noise. In our presentation, we talk about the motivation considering the weak values from the view of quantum foundations and show the nice property of the probability space independent of the observable via weak values. We construct the quantum measurement theory for the weak values. To conclude, the weak value is a useful tool in quantum information and quantum foundations despite its naming.

[1] Y. Shikano and A. Hosoya, arXiv:0812.4507.

Heisenberg uncertainty relations can be replaced by stronger ones

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(oral, section G)

Two uncertainty relations, one related to the probability density current and the other one related to the probability density, are derived and discussed. Both relations are stronger than the Heisenberg uncertainty relations. Their generalization to the multidimensional case and to the mixed states is also discussed.

Intensity-field correlation of single-atom resonance fluorescence

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We report measurements of an intensity-field correlation function of the resonance fluorescence of a single trapped Ba+ ion. An Ba+ ion is loaded into a linear Paul trap and is continuously laser-cooled. Detection of a photon prepares the atom in its ground state and we observe its evolution under interaction with a laser field of well defined phase. We record the regression of the resonance fluorescence source field. This provides a direct measurement of the field of the radiating dipole of a single atom and exhibits a strong non-classical behavior. In the setup an interference measurement is conditioned on a fluorescence photon detection. Thus, the recorded third-order correlation function demonstrates an aspect of wave-particle duality at the single-atom, single-photon level.

Identification of continuous variable entanglement and optimized quasi-probabilities

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(poster)

One important concept of the quantumness of nature are nonclassical correlations between the subsystems of a compound system. This quantum property is called entanglement. Physical systems are often described by continuous variables. Thus entanglement in these systems depends on a continuous number of degrees of freedom. In general a truncation to finite systems cause fake nonclassicalities. Despite this fact, we showed that the phenomenon entanglement can always be identified in finite systems [1]. Thus entanglement is a property which needs to be studied in finite systems only. Negative quasi-probability distributions are another concept of nonclassicality. The most prominent example is the Glauber-Sudarshan P function. This function is unique for every quantum state. Thus negativities in the P function are necessary and sufficient for nonclassical states. Quasi-distributions can be introduced for entanglement as well. But in general they are not unique – negativities are only necessary but not sufficient for entanglement. We introduce an optimization procedure for quasi-probability distributions which leads to an optimized quasi-distribution for entanglement [2]. Negativities in this optimized quasi-probabilities are sufficient for entanglement.

[1] J. Sperling and W. Vogel, *Verifying continuous-variable entanglement in finite spaces*, arXiv:0809.3197[quant-ph].
[2] J. Sperling and W. Vogel, *Representation of entanglement by negative quasi-probabilities*, arXiv:0811.4527[quant-ph].

Single-photon single-ion interaction in free space configuration in front of a parabollic mirror

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(oral, section E)

We theoretically investigate conditions for an experimental setup consisting of a single two-level ion trapped at the focus of a parabolic metallic mirror, under which the assumption about a free space mode structure of radiation field in vicinity of the atom is justified. We seek for the changes in the spontaneous emission rate of the atom resulting from the presence of the parabolic boundary conditions, within the vectorial model of light by including the polarization degree of freedom. We assume single-photon single-atom interaction. Depending on the characteristic parameters of the setup it provides us with either free space configuration or a tailored electromagnetic reservoir near the atom.

Generation of entangled photon pairs in chirped periodically-poled nonlinear crystals

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(poster)

Using a rigorous quantum model a comprehensive study of physical properties of entangled photon pairs generated in spontaneous parametric down-conversion in chirped periodically-poled crystals is presented. Spectral, temporal, as well as spatial characteristics of photon pairs are analyzed. Spectral bandwidths, photon-pair flux, and

entanglement area can be effectively controlled by chirping. Quantification of entanglement between photons in a pair is given. Splitting of entanglement area in the transverse plane accompanied by spectral splitting has been revealed. Using the model temperature dependencies of the experimental intensity profiles reported in literature have been explained. Attention is also paid to poled structures with randomly distributed boundaries.

Quantum uniqueness

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(oral, section G)

It is well known, that the quantum world can demonstrate fascinating phenomena which do not exist classically. In the area of quantum information the prominent examples are entangled states, violation of Bell inequality, no-cloning principle, etc. Initially they appeared as purely theoretical work, but later found important applications, e.g. in cryptography and computations. In this work we would like to highlight another interesting quantum feature which also has no classical analog: uniqueness of quantum systems. The no-cloning principle says that a perfect copy of an arbitrary a priori unknown quantum system cannot be created. The question we would like to discuss is in a certain sense complementary to it: if the perfect copy exist at all? Following everyday experience, we say that systems A and B are perfect copies of each other if there is no way to distinguish between them, i.e. the systems have absolutely the same properties and show absolutely the same manifestations. Otherwise, if for a given system A one cannot find such a perfect copy B, then we say that the system A is unique. In classical world existence of the perfect copy is possible in principle, and therefore no classical system is unique. As we show in this talk, the perfect copy of any quantum system doesn't exist even in principle, and thus all quantum systems are unique. It is important to note, that we do not mean uniqueness of a quantum state. Nothing restricts us from producing identical states in general, e.g. if one a priori knows the state, then it is possible to create an arbitrary number of its clones. Speaking about uniqueness, we refer to the external characteristics which can be objectively observed, or measured. In other words, we address a question if it is possible that two quantum systems always show exactly the same measurement outcomes.

Practical coherent state quantum key distribution with multi-letter alphabets

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(oral, section F)

Quantum key distribution (QKD) is a procedure of information exchange between two parties, the sender Alice and the receiver Bob, which allows to distribute absolutely secure data between them. The distinctive part of QKD with respect to classical communication is use of a quantum information channel. In this case secrecy is based on the fundamental laws of quantum mechanics. Mathematically, carriers of informational can be classified as discrete variable (DV) and continuous variable (CV), although physically they can be of various kind: single photons, weak coherent pulses, squeezed states and other systems where a signal possesses essentially quantum properties. In the case of DV QKD, it has been shown that some extensions of the standard four-letter BB84 protocol to higher number of letters in the quantum alphabet can improve performance of QKD in terms of higher critical error rate. In this talk we discuss our new protocol for CV QKD, which is also based on multi-letter alphabets [1]. We present security analysis of the protocol and show how the key rate depends on the number of letters. Additionally, we take into account imperfections of the practical realization of QKD (realistic non-perfect error correction, fluctuations of parameters of the experimental setup, biased random number generator, etc) an show how they affect the key rate.

[1] arXiv:0902.1895.

Distillation of continuous variable entanglement from Gaussian states

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(oral, section B)

Entanglement is an essential resource for various quantum communication protocols. While most quantum communication protocols rely on the usage of highly entangled states, in practice one meets less entangled or noisy mixed states due to imperfections or decoherence. For such a situation entanglement distillation was devised as a protocol to recover entanglement from distributed noisy entangled states by using local operations and classical communication. So far in the continuous variable setting no experimental demonstrations achieving the distillation of entanglement from Gaussian states have been reported. This is because of the no-go theorem of entanglement distillation with Gaussian means: It has been shown that it is not possible to distill entanglement from Gaussian states by using local Gaussian operations and classical communication. Hence for that purpose we need some non-Gaussian operations, which are in general experimentally more demanding. Some experiments distilling entanglement from non-Gaussian states by Gaussian operations have already been reported. However due to the importance of Gaussian states in continuous variable quantum information the demonstration of entanglement distillation from Gaussian states has been a significant experimental milestone to be achieved. Here we experimentally demonstrate the distillation of continuous variable entanglement from Gaussian states. We generated a squeezed vacuum by using an optical parametric oscillator and split it on a 50/50 beam splitter to make a two-mode entangled Gaussian state. As the local non-Gaussian operation for distillation we tapped a small part of one of the modes to be detected by an avalanche photo diode (APD). Conditioned on the photon detection by the APD the two-mode state was brought into some non-Gaussian state. We reconstructed the two-mode states generated in this way by means of homodyne tomography and evaluated their entanglement in terms of the negativity of entanglement. As a result we observed a clear increase of entanglement compared to the original Gaussian states.

An approximate beamsplitter interaction between light and matter

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(poster)

Beamsplitters play vital roles in quantum optics and quantum information for their simplicity and multiple potential uses, such as creating two-mode squeezed states of light, adding/subtracting photons and many others. Although many quantum information protocols require an interaction between light and matter, a similar atom-light beamsplitter transformation has not been realised so far. Here we explore the possibility of achieving a lossless beamsplitter interaction between an incident light field mode and a macroscopic atomic spin ensemble via two QND interactions. In the case of the atoms, the quadratures represent the re-scaled collective spin operators. The multi-pass QND protocols were studied in [1] for their use in light-state retrieval. Merely two independent subsequent light passes are required in our scheme to generate a beamsplitter-like interaction between light and matter, without any need of interference between the modes. We explore the conditions on the interaction coupling constant and the quadrature distributions which best approximate this interaction to that of a beamsplitter. We then test for which states this approximation holds. Finally we consider possible applications of this effective beamsplitter interaction. If the coupling constant is small, it may be possible to use this scheme to increase the entanglement between two entangled atomic ensembles. This could possibly be done by performing beamsplitter interactions on both ensembles, combining the emerging light beams on a real beamsplitter and taking a measurement of one of the light modes. Alternatively, if the fidelity of the interaction remains high as the coupling strength tends to 1/2 then this interaction approaches a 50:50 beamsplitter, which has many potential applications in the world of quantum optics.

[1] K. Hammerer, A. Sorensen and E. Polzik, arXiv:0807.3358.

Multi-photon and entangled-photon imaging and lithography

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(oral, section D, **invited** *)*

Nonlinear optics, which governs the interaction of light with various media, offers a whole raft of useful applications in photonics, including multiphoton microscopy and multiphoton lithography. It also provides the physicist with a remarkable range of opportunities for generating light with interesting, novel, and useful properties. As a particular example, entangled-photon beams generated via spontaneous optical parametric down-conversion exhibit unique quantum-correlation features, and coherence properties, that are of interest in a number of contexts, including imaging. Photons are emitted in pairs in an entangled quantum state, forming twin beams. Such light has found use, for example, in quantum optical coherence tomography, an imaging technique that permits an object to be examined in section. Quantum entanglement endows this approach with the remarkable property that it is insensitive to the even-order dispersion inherent in the object, thereby permitting sectioning to be achieved at higher resolution, and greater depths, than can otherwise be achieved. Although based on an esoteric feature of quantum mechanics, this technique is expected to have useful applications in biology and medicine. We discuss a number of techniques in which multiphoton and entangled-photon interactions offer advantages.

How can we control the frequency and spatial properties of multiphoton quantum states?

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(oral, section D, **invited** *)*

One important aspect of the successful implementation of most quantum optics applications is the ability to shape all the relevant properties of the quantum states involved, i.e., frequency, spatial shape and polarization and the interplay among all of them. Importantly, we should be able to generate the desired quantum states in any frequency band of interest and with the most efficient nonlinear crystals available. Here we demonstrate several techniques that enable tunable and full control of the bandwidth (from a few gigahertz to hundreds of nanometers), the frequency correlations of paired photons (anti-correlated, correlated and even uncorrelated), the coherence properties (control of the first order coherence of a light beam in a tunable way) and the spatial shape (from multimode entanglement to spatial separability) of single photon and multiphoton states. We also discuss how the light generated using these techniques can enlarge the potential applications in areas as diverse as Multidimensional Quantum Optics, Remote Sensing with quantum illumination or Optical Coherence Tomography.

Generation of macroscopic singlet states in atomic ensembles

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(oral, section E)

We study squeezing of the spin uncertainties by quantum non-demolition (QND) measurement in non-polarized spin ensembles. The QND measurement is based on atom-light interaction and subsequent measurement of light. Unlike in the case of polarized ensembles, the QND measurements can be performed with negligible back-action and produce squeezing even in the limit of strong measurement. Together these allow for the detection of large scale entanglement with a generalized spin squeezing criterion described in [1]. It is an important point that the scheme works for particles with a spin larger than 1/2, such that all j_z eigenstates within the atoms are populated. The entanglement criterion detects entanglement between the particles, and it is insensitive to the entanglement of the elementary spin-1/2 particles within the spin-1 or spin-2 atoms. The generated spin states approach many-body singlet states, and contain a macroscopic number of entangled particles, even when individual spin is large. We estimate the achievable spin squeezing for achievable experimental parameters for cold atomic ensembles. We introduce the Gaussian treatment of unpolarized spin states, which makes it possible to model large quantum systems for which direct quantum mechanical modeling is not possible. For the lossless case, we confirm our finding with comparison to the exact model.

[1] G. Toth et al., Phys. Rev. Lett. 99, 250405 (2007).
[2] G. Tóth and M. W. Mitchell, *Generation of macroscopic singlet states in atomic ensembles*, arxiv:0901.4110.

Comparison of uncertainty relations in quantum mechanics and signal processing

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(poster)

The Heisenberg's Uncertainty Relations (HUR) reflect the probabilistic description of particles, i.e. the essence of the quantum mechanics. Mathematically those relations are equivalent to Fourier Uncertainty Relation that connects the spreading of the signal and it's spectrum

[1,2]. Regrettably, the quantum mechanics textbooks usually omit the calculation and interpretation of HUR even in the case of simple quantum well tasks. Furthermore, the signal processing community has nearly totally forgotten the Fourier Uncertainty. The present study tries to correct those shortcomings. We explain why the Heisenberg-Fourier type uncertainty has not found noticeable application in signal processing. We offer a different formulation for uncertainty relation that may be used in signal processing and in quantum mechanics. In contrast to Heisenberg-Fourier type inequality this formulation specifies the limit for the uncertainty product if the number of signal pulses or wavefunction oscillations is increased. Additionally we show that in the parabolic quantum well the coordinate-momentum uncertainty product behaves as a quantised variable.

[1] C. L. Tang, *Fundamentals of quantum mechanics.* Cambridge Univ. Press, 2005.
[2]. A. Udal, V. Kukk, E. Velmre and M. Klopov, *Quantum mechanical transforms between x- and k-space as a signal processing problem.* Proc. of Int. Baltic Electronics Conf. BEC2008, p. 71 (available in IEEE Xplore).

Multi-path entanglement of two photons

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(oral, section D)

We present a novel optical device that enables the collection into eight single mode fibers of two photons entangled in many optical paths. The photons are generated by a spontaneous parametric down conversion (SPDC) emission of a Type I phase-matched nonlinear crystal operating under the excitation of a continuous wave laser. The collecting device is based on an integrated system of eight graded-index lenses glued onto single mode optical fibers. By this device four pairs of correlated k-modes have been selected to generate a two qudits (with d=4) entangled state encoded in the longitudinal momentum degree of freedom of the two photons. The multi-path entangled state has been characterized by a chained system of interferometers creating a complete indistinguishability between the four modes on which each photon can be emitted. The multi-path photon entanglement device realized in this experiment is expected to find important applications in modern quantum information technology. For instance, multiqubit states, entangled in the path of the photons, can be generated by using this system together with an integrated optical waveguide circuit. Furthermore, the same device represents a viable solution for the realization of a 'quasi-deterministic' source of heralded single photons emitted along one half of the SPDC modes and triggered by the photons emitted along the other half of correlated modes. The same device, allowing the maximization of the photon pair emission of for a given value of the pump power, can be also used to efficiently transmit, to many pairs of users and over long fiber distances, time-bin entanglement, which is not affected by thermal or mechanical fiber instabilities.

Nonadiabatic coherent evolution of two-level systems under spontaneous decay

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(oral, section E)

In this work [1] we extend current perspectives in engineering reservoirs by producing a time-dependent master equation leading to a nonstationary superposition equilibrium state that can be nonadiabatically controlled by the system-reservoir parameters. Working with an atom trapped inside a nonindeal cavity we first engineer effective interactions, which allow us to achieve two classes of decoherence-free evolution of superpositions of the ground and excited atomic levels: those with time-dependent azimuthal or polar angle. As an application, we generalise the purpose of an earlier study [2], showing how to observe the geometric phases acquired by the protected nonstationary states even under a nonadiabatic evolution.

[1] Phys. Rev. Lett. 102, 073008.
[2] Phys. Rev. Lett. 96, 150403 (2006).

Continuous-variable entanglement

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(oral, section B, **invited** *)*

In the field of Quantum Optics the discussion of nonclassical effects of radiation is usually based on the occurrence of negativities in the quasi-probability distribution or P function of Glauber and Sudarshan. Recently we could directly reconstruct such a nonclassical distribution, based on experiments with single-photon added thermal states [1]. In cases of a singular P function, when the reconstruction is impossible, the inspection of the characteristic function is a powerful method to demonstrate the corresponding nonclassicality [2]. More generally, nonclassical effects have also been studied from the viewpoint of quantum field theory [3]. Whereas the consideration of continuous-variable (CV) systems is natural for dealing with nonclassicality, entanglement is often studied in finite dimensional systems or for Gaussian quantum states. A general approach to identify entanglement of non-Gaussian CV quantum states could be developed, which applies to states showing negativities in the partial transposition [4]. Making use of the general structure of entanglement witnesses, general and optimized entanglement conditions have been derived [5], which also identify bound entanglement. The importance of quasi-probabilities for the characterization of nonclassical effects leads to the question whether such methods are relevant in the context of entanglement. The P function of entangled states necessarily exhibits negativities. However, these negativities are insufficient to demonstrate entanglement. Here we consider quasi-probabilities whose positivity is sufficient to demonstrate the separability of quantum states. After performing an optimization procedure, the positivity and the existence of negativities of the optimized quasi-probabilities strictly identifies both separability and entanglement, respectively.

[1] T. Kiesel, W. Vogel, V. Parigi, A. Zavatta and M. Bellini, Phys. Rev. A 78, 021804(R) (2008).
[2] T. Kiesel, W. Vogel, B. Hage, J. DiGuglielmo, A. Samblowski and R. Schnabel, Phys. Rev. A 79, 022122 (2009).
[3] W. Vogel, Phys. Rev. Lett. 100, 013605 (2008).
[4] E. Shchukin and W. Vogel, Phys. Rev. Lett. 95, 230502 (2005).
[5] J. Sperling and W. Vogel, Phys. Rev. A 79, 022318 (2009).
[6] J. Sperling and W. Vogel, arXiv:0811.4527v2 [quant-ph].

Quantum systems with finite Hilbert space

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(oral, section A)

A quantum system where the position and momentum take values in Z(p) (the integers modulo p) is considered. Displacements and Wigner and Weyl functions in this context, are discussed. A quantum system where the position and momentum take values in the Galois field $GF(p^n)$, is also considered. The Heisenberg-Weyl group of displacements and the group $Sp(2, GF(p^n))$ of symplectic transformations, are studied. Frobenius symmetries is a unique feature of these systems, which has no analogue in the harmonic oscillator formalism. Quantum engineering of these systems from a chain of n spins (with j=(p-1)/2) which are coupled in a special way, is discussed.

Universal continuous variable quantum computation in the micromaser

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(oral, section B)

We will describe how to achieve universal continuous variable quantum computation in the One-Atom Maser (OAM). The OAM is a defining experiment of cavity QED and displays fundamental concepts of quantum mechanics. We first begin by describing what a computation is in physical terms. We then look at what a continuous variable is and what separates it from a discrete variable. Having looked at the classical case, we move on to the quantum analogue and how we can encode such a variable in the physical system we are using as our computer. We describe the OAM and indicate how we can encode our variables in this system. We then explore Universal computation in two different encodings and pick one encoding after looking at the states we have available to us. We then describe the operations required for universality and how we can achieve them in the laboratory. We will then have outlined what continuous variables are in quantum computation and how we can achieve Universal computation in the OAM.

Optimal measurement on noisy quantum systems

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(poster)

Recently many technologies of controlling and transferring quantum states have developed. However no process of them can operate without the quantum states are disturbed by the environment. These noise from environment cause serious effect on quantum information processing. Then the quantum estimation on noisy quantum states

is important. However optimal method for getting information from noisy quantum states is not fully understood. In this research, we show that what measurement is optimal for estimating the original quantum states from the noisy states. We use the Fisher information as measure of the optimality. We consider the quantum systems are the Hilbert spaces of arbitrary finite dimension and noise are implemented as CPTP map. For arbitrary CPTP map, we derive the optimal measurement for getting the information about the input state from the output state and calculate the Fisher information by the optimal measurement.

Multiphoton entanglement - tools and toys

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(oral, section D, **invited** *)*

Multiphoton entanglement is the mandatory resource for multi-party quantum communication. However, so far, experimental demonstrations usually suffer from low photon count rates and the lack of flexible experimental setups. Moreover, with the increasing complexity of the implemented quantum states their analysis becomes more and more difficult. Here we give an overview of our recent developments, aiming to cure some of the drawbacks of current approaches. We were able to observe a multitude of important quantum states with the same setup, thus, adding flexibility to multiphoton state observation. Furthermore, we achieved a speed-up in the state analysis by employing tailored operators, which exploit particular properties of entangled quantum states. Finally, we could perform six-photon experiments with reasonable count rates by introducing resonant en-

hancement of the UV-pump pulses needed for spontaneous parametric down conversion. These methods add to a powerful toolbox for future multi-photon entanglement studies.

Heisenberg-limited interferometry - how easy can it get?

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(oral, section C)

The interferometric measurement of an optical phase is an indispensable tool in metrology, used in length measurement, optical characterization and a myriad of other applications. The most fundamental quantum limit to such a measurement is the Heisenberg-limit: the uncertainty or standard error $\delta(\phi)$ from a single measurement of phase is bounded below by $(1/2)(1/\delta(n))$, where n is the number of photons passing through the phase shift. If we denote N the maximum number of photons that pass through the phase shift, the achievable bound is π/N. It has generally been assumed that achieving this limit requires large-N multiphoton entangled states like NOON states. However, because photons are identical and indistinguishable, the crucial resource is actually the number of photon-passes — we can pass the same photon more than once through the phase shift as long as we count each pass as contributing to the total. The number of passes cannot however be kept fixed, as that would result in an ambiguous phase estimate, just as occurs from a NOON state. Rather, it must change over the course of a single measurement. We have used this idea to experimentally demonstrate Heisenberg-limited-scaling interferometry for the first time [1], using an adaptive measurement scheme inspired by the quantum phase estimation algorithm. Now we have shown, theoretically and experimentally, that by careful distribution of resources, it is possible to attain Heisenberg-limited-scaling even without adaptive measurements. Our algorithms are equally applicable to NOON states as they are to single-photons with multiple passes. For N exponentially large, the former have the disadvantage of requiring exponential energy, the latter of requiring exponential time.

[1] Higgins et al, Nature 450, 393 (2007).

Near-optimal state discrimination of optical coherent states

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(oral, section C)

Optimal discrimination of non-orthogonal quantum states is one of the fundamental tasks in quantum detection theory. For weak coherent states, the standard detection schemes, namely homodyne detection and the Kennedy receiver, are not able to achieve error free sensitivity in principle. Both schemes do not even reach the optimal bound for the minimum average error. We propose and experimentally realize a novel detection strategy for the discrimination of two optical coherent states. We present the experimental comparison of the new strategy with standard detection schemes and demonstrate, that the new receiver surpasses both standard approaches for any signal amplitude. [1] An interesting extension is the discrimination of a coherent state alphabet consisting of four phase covariant coherent states equally separated in phase by $\pi/2$. This modulation pattern, known as quadrature phase-shift keying, is commonly used for high speed classical communication as well as relevant for quantum key distribution. We propose a hybrid system composed of a homodyne detector and a modified Kennedy detector where the latter one is controlled by the outcome of the former one: The measurement outcome of the homodyne detector reduces the alphabet from four states to two states which are then discriminated with the adapted Kennedy detector. We show that in theory this hybrid receiver outperforms the heterodyne receiver for signal states with average photon numbers larger than about 1.5.

[1] C. Wittmann et al., Phys. Rev. Lett. 101, 210501 (2008).

Nonlinear Faraday effect with cold atoms

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(oral, section E)

We report on our recent experiments with nonlinear Faraday effect (NLFE) in a sample of cold atoms. NLFE is the optical nonlinear phenomenon based on quantum coherences between magnetic (Zeeman) sublevels. When these sublevels are associated with long-lived atomic ground state coherences, the effect manifests itself with very narrow resonances leading to ultra-sensitive optical magnetometry and also to quantum information storage and processing. Previous work on NLFE has been mostly devoted to room temperature atomic vapors in paraffin coated or buffer-gas-filled glass cells. However, cold atoms may have even slower relaxation rate and therefore offer a promising alternative for NLFE. Yet, there has been comparatively limited work in this area of research. We demonstrate NLFE in a sample of cold 85Rb atoms cooled in a magneto-optical trap to about 100 μK. By working with ground-state coherences, we are able to create nonlinear magneto-optical response with extremely weak light and magnetic fields (μW and mG ranges), and yet we achieve magneto-optical rotation in excess of 5 degrees. Moreover, the magneto-optical rotation reveals a time dependence of the ground state coherences, which gives information as to their formation and evolution in time. This may find applications for studying time evolution of such quantum superpositions. Furthermore the same technique can be used as a diagnostic tool by mapping in time the transient magnetic fields resulting from the decaying trap field within the volume of the cold atom sample.

[1] D. Budker, W. Gawlik, D. F. Kimball, S. M. Rochester, A. Weis and V. V. Yashchuk, Rev. Mod. Phys. 74, 1153 (2002).
[2] S. Pustelny, A. Wojciechowski, M. Gring, M. Kotyrba, J. Zachorowski and W. Gawlik, J. Appl. Phys. 103, 063108 (2008).

Measurements incompatible in Quantum Theory cannot be measured jointly in any other local theory

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(oral, section G, **invited** *)*

It is well known that jointly measurable observables cannot lead to a violation of any Bell inequality - independent of the state and the measurements chosen at the other site. In this letter we prove the converse: every pair of incompatible quantum observables enables the violation of a Bell inequality and therefore must remain incompatible within any other no-signaling theory. While in the case of von Neumann measurements it is sufficient to use the same pair of observables at both sites, general measurements can require different choices. The main result is obtained by showing that for arbitrary dimension the CHSH inequality provides the Lagrangian dual of the characterization of joint measurability. This leads to a simple criterion for joint measurability beyond the known qubit case.

Ultra-bright narrow-band down-conversion source for atom-photon interaction

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(poster)

Many proposed applications of quantum communication and quantum metrology rely on the availability of entangled photon pairs. While photon pairs generated in spontaneous parametric down-conversion (SPDC) do not fulfill the spectral requirements for efficient interaction with atomic systems, the rate of photons resonant to an atomic transition can be greatly enhanced when the SPDC source is operated inside an optical cavity. This design not only implies the advantage of enhanced down-conversion into the cavity modes that are spectrally narrow enough to be compatible to atomic resonances. Furthermore the cavity also defines the spatial mode of the photon pairs that can therefore be coupled into single-mode fibers with high efficiency. Our setup [1] consists of a bow-tie cavity with a periodically poled KTP crystal as nonlinear medium. It is phase-matched for parametric down-conversion in order to generate photon pairs at the D1 transition of atomic rubidium at 795 nm. At a low pump power of 0.2 mW a coincidence rate of 34 000 pairs/s is detected making this setup one of the brightest sources of pairs of indistinguishable photons. In order to quantify the degree of distinguishability of the two photons of a pair a Hong-Ou-Mandel interference experiment was performed showing a visibility of 96 %. After filtering the longitudinal mode at the rubidium transition frequency using either filter cavities or atomic filters, the created photon state will be exploited to measure phase shifts in a hot rubidium vapor. In such a phase estimation it is in principle possible to reach the Heisenberg limit when N00N states, like the generated photon-pair state, are used as input.

[1] F. Wolfgramm et al., Opt. Express 16, 18145 (2008).

Protection of continuous variable entanglement via passive operations

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(poster)

To date most work on entanglement has concerned finite dimensional quantum systems. The research reported here is a part of a program to improve our understanding of entanglement and decoherence in continuous variables systems. We are considering general Gaussian dissipative channels (encompassing the description of thermalisation by contact with a reservoir) acting on Gaussian states of many modes. In an initial attack on the problem we are considering two mode squeezed states created either by directly using a non-degenerate parametric process or by superposing a single mode squeezed state at a beam splitter. In the former case, thermal noise and losses act on the entangled two mode squeezed state. In the latter case, they act on the separable product of initial single mode squeezed states. Given a fixed amount of noise, we then compare decoherence produced in the two cases in terms of final entanglement and purity. Hence we will identify optimized strategies to create entanglement depending on the noise and system's parameters.

Long-distance quantum entanglement experiments

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(oral, section D, **invited** *)*

Experiments using the quantum link between the Canary Islands of Tenerife and La Palma allow detailed tests of entanglement. Most recently, both photons of an entangled state could be transmitted with high fidelity despite the high attenuation of about 70 dB. Another experiment for the first time closed a loophole in Bell experiments related to Bell's requirement that the choice of measurement must be free and random, i.e. uninfluenced by the photon emission at the source. This is achieved by ensuring space-like separation of the decisions what will be measured from the emission event. In another series of experiments a number of nonlocal delayed choice type experiments were performed. There one of two entangled photons was send through an interferometer. The other photon was nonlocally subjected to a measurement which either projected the other photon into a superposition of both paths or into a definite path. Finally, I will also report a related two-photon interference experiment.

Process POVM: A mathematical framework for description of quantum process experiments

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(oral, section F, **invited** *)*

We shall introduce the mathematical framework for the description of measurements of quantum processes. Using this framework the process estimation problems can be treated in the similar way as the state estimation problems, only replacing the concept of positive operator valued measure (POVM) by the concept of process POVM (PPOVM). In particular, we will show that any measurement of qudit channels can be described by a collection of effects (positive operators) defined on two-qudit system. However, the effects forming a PPOVM are not normalized in the usual sense. We will briefly demonstrate the usage of this formalism on three particular examples: 1) equivalence of perfect channel discrimination with specific unambiguous state discrimination 2) unambiguous comparison of unitary channels 3) MaxEnt for process estimation from incomplete data. In conclusion, we shall discuss the limitations of the PPOVM framework.

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