European Science Foundation
Standing Committee for Physical and Engineering Sciences (PESC)

ESF PESC EXPLORATORY WORKSHOP

Long-distance Quantum Communication Networks with Atoms and Light

Scientific report

Prague, Czech Republic, 9-12 April 2005

Convened by:
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COVAQIAL

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Executive summary

Quantum information theory has developed dramatically over the past few years, driven by the prospects of quantum-enhanced communication and computation systems. It exploits the intrinsic parallelism and large space capacity of quantum mechanics to perform tasks that cannot be realized with classical physics. In particular, the domain of quantum communication seems to be very promising for practical applications in a near future. However, present-day quantum key distribution systems can operate only over the distances of several tens of kilometers, which may severely limit their practical applicability. One of the major challenges in the field presently is to develop long-distance quantum communication networks which allow secure quantum communication over arbitrarily long distances.

The aim of the Exploratory Workshop was to investigate and discuss a novel and very promising approach to the development of quantum communication networks based on the use of the quantum continuous-spectrum variables carried by a light mode or an atomic ensemble.

Quantum continuous variables seem to be particularly suitable for quantum communication since they offer large bandwidth and may be easier to manipulate than quantum bits. It is actually sufficient to process squeezed states of light into linear optics circuits in order to perform various quantum information processes over continuous variables, including quantum teleportation and quantum key distribution. Another significant advantage of this new paradigm is the fact that, unlike discrete atomic spins, distant atomic continuous-variable systems can be entangled and that a light-atoms quantum state exchange can be performed at the level of continuous variables. The resulting atomic quantum memory for light is thought to be a crucial component of the future quantum communication networks.

The potential of this novel approach for quantum communication has been recently recognized by the European Commission which approved a STREP (Specific Targeted Research or Innovation Project) named COVAQIAL (COntinuous VAriable Quantum Information with Atoms and Light) which started in September 2004. The Exploratory Workshop was partially financed from the budget of COVAQIAL, and the first annual meeting of COVAQIAL took place during the workshop. The joint support by ESF and COVAQIAL provided the necessary synergy allowing to invite representatives of all major European groups involved in the field of quantum information processing with continuous variables.

The workshop was convened by Jaromir Fiurasek (Department of Optics, Palacky University, Olomouc, Czech Republic) and Nicolas J. Cerf (QUIC, Université Libre de Bruxelles, Belgium). The local organizing team included also Radim Filip and Zdenek Hradil (Department of Optics, Palacky University, Olomouc, Czech Republic). The event took place in Prague, Czech Republic.

The program of the workshop included 17 talks lasting 35 minutes each + 10 minutes devoted to discussions. The participants who did not give talks had the opportunity to present their work during two poster sessions, including respectively 9 and 8 posters. The poster sessions as well as the long coffee and lunch breaks facilitated lively and fruitful discussions on the various topics addressed by the workshop.

A special website dedicated to the workshop has been established and is available at:
http://optics.upol.cz/workshop/

Scientific content

Quantum communication holds the great promise of unconditionally secure exchange of information among distant parties. The security is of paramount importance in applications such as Internet commerce. Current quantum key distribution (QKD) systems can guarantee secure communication over distances of several tens of kilometers. The main obstacle preventing the extension of the communication distance lies in the unavoidable losses and noise in the communication lines (telecom optical fibers) and detectors. A long-distance secure quantum communication between two parties is nevertheless possible using so-called untrusted quantum repeaters, which combine the distribution of quantum entanglement over short distances, quantum memory, and entanglement purification and swapping in order to establish quantum entanglement over very long distances.

The aim of the Exploratory Workshop was to investigate and discuss a novel and very promising approach to the development of quantum communication networks and quantum repeaters based on the use of quantum continuous-spectrum optical and atomic variables.

The scientific topics discussed during the workshop can be divided into several mutually related areas:

Interaction of light with atomic ensembles and quantum memory for light

The quantum memory for light is a device that can store the quantum state initially carried by an optical beam. The quantum memory represents a crucial component of the quantum repeaters and is necessary for their scalability. **Eugene Polzik** reported on the groundbreaking first experimental demonstration of a quantum memory for light, which exploits an off-resonant interaction of a light beam with an ensemble of Cesium atoms hold in a glass cell at a room temperature. The state of light is transferred onto coherences among the atomic ground states. The current life-time of the memory is about 5 ms, but it may be extended to several seconds using cold trapped atoms. Further details of the quantum memory experiment were presented by **Jacob Sherson**.

Tomas Opatrny described a method how to enhance the capacity of the atomic quantum memory by exploiting several coherences among the magnetic sublevels of the ground state manifold. This technique also provides a novel direct method of swapping the quantum state of light and atoms, and it allows one to create an entangled state of atoms and light.

Klemens Hammerer presented an experimentally feasible protocol for the teleportation of the quantum state of light onto atoms. The scheme starts with the creation of an entangled state of atoms and an auxiliary light beam, followed by a Bell-type measurement of the light beam to be teleported and the auxiliary light beam. Finally, the collective spin of the atomic ensemble is rotated according to the measurement outcome. The possibility to implement this experiment in the group of E. Polzik was discussed during the workshop.

The issue of atom-light coupling was also addressed by several other participants. In particular, **Elisabeth Giacobino** described experiments where the interaction of light with atomic ensembles held in a cavity is exploited to generate squeezed and entangled states of light. **Frederic Grosshans** pointed out that the quantum memory is also important in the context of quantum key distribution with coherent states, where it would allow for more powerful eavesdropping attacks.

Generation of squeezed and entangled states

Squeezed states play a fundamental role in quantum information processing with continuous variables as they provide the necessary resource required in many protocols and applications. **Thomas Coudreau** described a novel method of generation of two-mode squeezed states with a self-phase-locked optical parametric oscillator (OPO). The idea is to insert a wave plate into the OPO cavity rotated such that it slightly couples the two polarization modes. This coupling ensures degenerate operation where the frequencies of the signal and idler beams are equal.

Gerd Leuch suggested that the phenomenon usually referred to as “single-mode squeezing” is in fact also a squeezing of two modes, namely two sidebands at radio-frequency Ω with respect to carrier frequency ω. The two sidebands can be spatially separated using a strongly unbalanced beam splitter with the arm length difference of a few meters. The manipulation and separation of the sidebands has been demonstrated experimentally by the Erlangen group in collaboration with colleagues from Australia. This work paves the way to exploiting the inherently multimode structure of squeezed light in the frequency domain.

Roman Schnabel reported on generation of squeezing at a very low frequency, below 100 kHz. Besides being of interest for quantum information processing, this source could be potentially used in the next generation of gravitational wave detectors, which are extremely large interferometers whose sensitivity is ultimately limited by quantum noise. The resolution of these detectors can be enhanced by sending squeezed light into one port of the interferometer and squeezing at low frequencies is essential because the astronomical sources of gravitational waves are expected to radiate at these low frequencies.

Quantum cryptography

An experimental demonstration of a quantum key distribution protocol based on the transmission of coherent states and heterodyne detection was reported by **Thomas Symul**. The great advantage of this approach is that it does not require an active switching of measurement bases, and can run at a very high repetition rate of several tens of MHz. The protocol is rather involved, and includes cleverly designed post-selection to enhance the security of the protocol. According to Dr. Symul, this guarantees that the protocol is secure even for transmission losses highly exceeding 50%, i.e. 3 dB. A very lively discussion concerning the security of this protocol took place right after the talk. The experimental implementation of a similar protocol also involving post-selection and passive base switching was presented by **Stefan Lorenz**, and the security aspects of this protocol were discussed by **Norbert Luetkenhaus**.

Thierry Debuisschert presented new technological developments of the Orsay QKD scheme which is based on the transmission of coherent states followed by homodyne detection of one of the two conjugate quadratures. The newly developed experimental setup operates at telecom wavelength, and is suited for integration into the telecom optical fiber networks.

Antonio Acin and **Frederic Grosshans** discussed the security aspects of quantum key distribution protocols with continuous variables. **Antonio Acin** showed that it is possible to distill a secret key secure against any attack from sufficiently entangled Gaussian states with non-positive partial transposition. Moreover, all such states allow for key distillation when the eavesdropper is assumed to perform finite-size coherent attacks before the reconciliation process.

Frederic Grosshans addressed the issue of collective attacks on CV-QKD protocols. These attacks, overlooked in previous security studies, give a finite advantage to the eavesdropper in the experimentally relevant lossy channel, but are not powerful enough to reduce the range of the reverse reconciliation protocols. Moreover, adopting a generic security proof of Christiandl, Renner and Ekert, it is possible to obtain unconditionally secure secret key generation rates for several CV-QKD protocols.

Generation of non-Gaussian states

One of the main difficulties in developing quantum repeaters for continuous variables is that the entanglement of Gaussian states cannot be distilled using Gaussian operations only. Recently, the group of Philippe Grangier in Orsay demonstrated the de-Gaussification of single-mode squeezed states by means of a photon subtraction. This landmark experiment paves the way to experimental CV entanglement distillation. The conditional photon subtraction is achieved by reflecting a tiny portion of the beam onto a single-photon detector, whose click indicates the successful removal of one photon from the beam. The advantages of this technique lie in its robustness: it works well even with realistic inefficient detectors that cannot resolve the number of photons in the field. **Alexei Ourjoumtsev** presented recent improvements of the experimental setup in Orsay. The parameters have been improved so that it should now be possible to generate highly non-classical states with negative Wigner functions.

Jaromir Fiurasek showed that using a sequence of conditional single-photon subtractions and coherent displacements, it is possible to prepare an arbitrary superposition of the first N Fock states from a squeezed vacuum state. This experimentally feasible scheme is very promising for the experimental engineering of highly non-classical states.

Austin Lund pointed out that the photon-subtracted single-mode squeezed state closely resembles a "small" Schrödinger cat state – a superposition of two coherent states with small coherent amplitude. He also suggested a method to merge these small Schrödinger cat states in order to obtain a Schrödinger cat state with rather large amplitude of the constituent coherent states. Using such states as a resource, it is possible to perform deterministic quantum computation with linear optics and single-photon detectors.

Quantum information processing

Ulrik Andersen described an experimental implementation of the optimal approximate Gaussian quantum cloning of coherent states. The experimental setup cleverly avoids the need for a parametric amplifier, which was previously assumed to be a key component for the cloning of coherent states. Half of the beam is sent to a heterodyne detector while the remaining half of the beam is displaced according to the measurement outcome and then split into two beams – the clones. This approach is very promising as it can be extended, e.g. to apply a squeezing operation to an arbitrary state using only a source of squeezed vacuum that is then combined on a beam splitter with the beam to be squeezed and subsequently measured by a homodyne detector.

Nicolas Cerf addressed the problem of evaluating the capacity of quantum Gaussian channels with memory, and showed that quantum entanglement can be used to enhance the capacity of these channels, in contrast with memoryless Gaussian channels. **Natalia Korolkova** proposed an entanglement concentration scheme for continuous variables based on the measurement of the Stokes parameter of the light beam and a feedback.

Assessment of the results, contribution to the future direction of the field

The workshop provided a platform for discussion among the leading European scientists working in the field of quantum information processing with continuous variables. This is a rapidly developing area of research, where Europe is playing a leading role as reflected by the recent groundbreaking experimental demonstrations of a quantum memory for light, quantum key distribution with coherent states, and de-Gaussification of squeezed states by European research groups. The workshop helped to strengthen this leading position of European science in this field, and allowed to establish new links and stimulate new collaborations among the various research groups in Europe.

The talks presented during the workshop provided a very up-to-date overview of the state of the art in this newly emerging research area in Europe, which greatly helped to identify and pinpoint the main challenges in the field. Most of the basic building blocks of the envisaged future quantum communication networks such as the quantum memory for light, the source of entangled two-mode squeezed states, quantum teleportation, and entanglement swapping have now been experimentally demonstrated in the laboratories.

One of the main forthcoming tasks is the integration of these basic building blocks into a quantum network. More specifically, the development and experimental implementation of entanglement distillation and purification schemes appears to be one of the biggest challenges. This truly interdisciplinary effort requires a close collaboration of experimentalists with theoreticians and of quantum opticians with atomic physicists.

A very promising future direction that emerged during the workshop could be called “hybrid” quantum information processing. This novel optical quantum information processing (QIP) paradigm combines the approaches developed in the fields of single-photon linear optics QIP and continuous-variable QIP, and benefits from their respective strengths. For instance, the quantum memory developed originally for continuous-variable states of light appears to be perfectly suitable also for the storage of single photon states.

Judging from the reactions of the participants, the workshop was a great success. The participants expressed very strongly their wishes that a workshop or conference devoted solely to continuous-variable QIP would be organized again next year. Professor Eugene Polzik agreed to organize such a conference in Copenhagen in the spring 2006.

WORKSHOP PROGRAMME

Saturday 9 April 2005

12:30-14:00 *Buffet lunch*

14:00-14:30 *Registration*

14:30-14:45 **Workshop opening**

14:45-15:00 **Presentation of the European Science Foundation (ESF)**
(Standing Committee for Physical and Engineering Sciences)

Chairman: **Nicolas Cerf**

15:00-15:45 **Elisabeth Giacobino**
Generation of continuous squeezed and entangled states

15:45-16:30 **Eugene Polzik**
Quantum interface between light and atomic ensembles

16:30-17:00 *Coffee break & discussion*

17:00-17:45 **Gerd Leuchs**
Sideband entanglement and continuous variable cryptography

Sunday 10 April 2005

Chairman: **Eugene S. Polzik**

09:00-09:45 **Tomas Opatrny**
Increasing the amount of information stored in atomic quantum memory

09:45-10:30 **Klemens Hammerer**
Teleportation exploiting multimode entanglement of light with atoms

10:30-11:00 *Coffee break & discussion*

Chairman: **Elisabeth Giacobino**

11:00-11:45 **Klaus Mølmer**
Entanglement of atomic samples via lossy optical transmission lines

11:45-12:30 **Ulrik Andersen**
Experimental quantum cloning of coherent states

12:45-14:15 *Lunch*

Chairman: **Zdenek Hradil**

14:30 – 15:15 **Antonio Acin**
Gaussian operations and privacy

15:15-16:15 **Poster session**

16:15-16:45 *Coffee break & discussions*

16:45-17:45 *Annual meeting of the EU project COVAQIAL*

Monday 11 April 2005

Chairman: **Gerd Leuchs**

09:00-09:45	**Nicolas Cerf** Capacity of bosonic Gaussian channels with memory
09:45-10:30	**Thomas Coudreau** Continuous-variables two-mode entanglement with a self phase locked OPO: experimental generation and characterization
10:30-11:00	*Coffee break & discussion*

Chairman: **Matteo G. A. Paris**

11:00-11:45	**Jaromir Fiurasek** Conditional generation of highly non-classical states via repeated photon subtraction
11:45-12:30	**Austin Lund** Techniques for generating interesting non-Gaussian states of light
12:45-14:15	*Lunch*

Chairman: **Tomas Opatrny**

14:30-15:15	**Thomas Symul** Quantum Cryptography without Switching of Measurement Basis
15:15-16:00	**Poster session**
16:00-16:30	*Coffee break & discussions*
16:30-17:00	**Poster session**

Tuesday 12 April 2005

Chairman: **Antonio Acin**

09:00-09:45	**Thierry Debuisschert** Continuous variable quantum cryptography at telecom wavelength
09:45-10:30	**Frederic Grosshans** Role of Quantum Memory in Continuous Variable Quantum Key Distribution
10:30-11:00	*Coffee break & discussion*

Chairman: **Fabrizio Illuminati**

11:00-11:45	**Natalia Korolkova** Quantum polarization for information encoding and storage
11:45-12:30	**Roman Schnabel** Generation and Applications of Squeezed Light from OPA
12:30-12:45	**Workshop closing**
12:45 – 14:15	*Lunch*

POSTER SESSION Sunday 10 April 2005

Konrad Banaszek
Hybrid decoherence-free subspaces for quantum communication over depolarizing channels

Thomas Coudreau
Towards CV quantum information processing with trapped ions

Radim Filip
Phase-insensitive quantum erasing

Fabrizio Illuminati
Entanglement and Purity in Continuous Variable Systems

Stefan Lorenz
Coherent state quantum key distribution with simultaneous polarization measurement

Norbert Lütkenhaus
Performance of quantum key distribution protocols based on coherent states and homodyne detection under realistic conditions

Julien Niset
Continuous-Variable Nonlocality without Entanglement

Alexei Ourjoumtsev
Towards the generation of optical Schrödinger cat states

Jacob Sherson
Experimental demonstration of quantum memory

POSTER SESSION Monday 11 April 2005

Radim Filip
Quantum non-demolition measurement saturates fidelity trade-off

Raul Garcia-Patron Sanchez
Generation of arbitrary sinlge-mode quantum states of light by repeated photon subtraction

Julien Laurat
Type II Optical Parametric Oscillator: a versatile source for continuous variable quantum correlations

Matteo G. A. Paris
Optimal quantum repeater

Stefan Scheel
Success and failure in LOQC

Norbert Schuch
Optimal generation of squeezing and entanglement with noisy channels

Rosa Tualle-Brouri
Quantum key distribution with coherent states at telecom wavelength

Jerome Wenger
Pulsed squeezed vacuum characterization with and without homodyning

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Statistical Information on Participants

The total number of participants was 35. Among them were 2 participants from Australia and the remaining 33 participants were from Europe. About half of the participants were members of the groups involved in the EU STREP project COVAQIAL. The participants represented a balanced mixture of experienced and junior researchers, and there were 14 young scientists (age below 35 years). There were 3 female and 32 male participants. The distribution of the participants according to the countries is shown in the table below:

Origin of the participants :

Country	# of participants
Australia	2
Belgium	3
Czech Republic	4
Denmark	3
France	9
Germany	8
Italy	2
Poland	1
Spain	1
UK	2
Total :	**35**