RESEARCH CONFERENCES

ESF-FWF Conference in Partnership with LFUI

Quantum Optics: From Photons and Atoms to Molecules and Solid State Systems

Universitätszentrum Obergurgl (Ötz Valley, near Innsbruck) • Austria

24 February - 1 March 2008

Chair: **Jörg Schmiedmayer**, TU-Wien, Atominstitut der Österreichischen Universitäten, Austria

Co-Chairs: **Hanns-Christoph Nägerl** & **Helmut Ritsch**, University of Innsbruck, AT

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Highlights & Scientific Report

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Conference Highlights

Please provide a brief summary of the conference and its highlights in non-specialist terms (especially for highly technical subjects) for communication and publicity purposes. (ca. 400-500 words)

A thorough understanding of quantum optics in its broadest sense has the potential to lead to new (quantum) technologies that will help define the 21st century; quantum information and quantum metrology are two prominent examples. Although most of the applications are still many years away, dramatic progress has been made laying the groundwork for projects at the laboratory level that demonstrate the concepts on a small scale.

One example is quantum communication, which enables unconditionally secure transmission of information. At the conference major steps towards realizing a 'quantum repeater' to faithfully connect communication channels were presented, which should allow eventually to extend quantum communication over much longer, perhaps global, distances.

Quantum optics systems also have demonstrated their potential for quantum computers. The conference heard about new experiments with superconducting quantum circuits, a remarkable progress that brings the heart of quantum optics into solid state devices and electronic (quantum) circuits. There was also great progress in high fidelity quantum gates in ion traps, which can be seen now as the ideal platform to build and research quantum logic components for future scalable quantum computers.

A third topic was quantum simulations, where the tools of quantum optics are used to 'build' well-controlled experimental models of theoretical concepts, which are in itself too hard to be solved either by analytic methods or by simulation on classical computers. Such quantum simulations hold the promise to give us insight into some of the great outstanding problems in solid state physics, like the mechanism behind high temperature superconductivity, or problems on quantum magnetism. The conference heard about how to build specific 'interactions' needed to build such simulation models in the laboratory, or how quantum coherence and its dynamics can be probed in low-dimensional systems.

Remarkable progress was reported in controlling and cooling mechanical oscillators close to the quantum regime, promising to put the 'quantum' into real world mechanics of small nano-objects in the very near future.

A special promise holds the demonstration of high fidelity Bloch oscillations by controlling atom-atom interactions. This opens the possibility for new ultra precise quantum measurements with BEC's, an aspect which was believed to be very difficult because of the non-linear nature of these systems.

Especial excitement was generated by young researchers, especially in the hot topic sessions, which were among the highlights of the conference. At these, very new science was discussed, science that was not even envisioned three years ago. Many results had not yet been presented elsewhere before.

The conference fulfilled its objectives by bringing together people in diverse fields of quantum science.

☐ I hereby authorize ESF – and the conference partners to use the information contained in the above section on 'Conference Highlights' in their communication on the scheme.

Scientific Report

Executive Summary

(2 pages max)

In the past years the field of quantum optics has begun to expand from its original domain covering basic photon(ic) and atom(ic) systems into the realm of molecular and solid state physics. Theory and experiment have progressed to the point where the traditional boundaries between the different areas have become less pronounced. The aim of this conference was to bring together scientists from these various fields now contributing to an increasing extent to quantum optics and adopting quantum optical approaches in order to study and discuss the similarities and synergies between the different realizations of quantum optical systems and to identify new trends and possible applications.

Quantum physics is fundamental for our understanding of nature, and it has thus been central for the development of new methods and technologies. Devices and applications are in general governed by classical physics, but more and more their basis is in the quantum world. Modern developments in the field of quantum optics and solid state physics show that quantum systems per se can be useful devices. For example, they can serve as small quantum computers or they can be used in a clock or interferometer for high-precision measurements. They find application in superconducting devices and can be used for secure quantum cryptography. A robust technological implementation of quantum physics has the potential to be one of the defining technologies of the 21st century.

Quantum physical concepts by themselves can have far reaching implications beyond their traditional applications. The concept of a quantum bit, contrasted to the classical bit, will force us to redefine our ways of classifying logical operations and consequently the complexity classes of computational and logical problems or even the concept of mathematical proofs. One of the great challenges in quantum optics today is to link different quantum systems to each other while preserving the quantum nature over the link. Another great challenge is to identify the border between the classical and the quantum world and to find ways to extend the quantum world into the mesoscopic regime.

The meeting was not only a forum to present the latest results but also served as crystallization point for new ideas in this rapidly developing field. There were 34 invited talks, and two special hot topic sessions of 9 contributed talks, selected from the submitted abstracts. These hot topic talks were mainly by young researchers, presenting the latest ideas and theoretical and experimental results. There were two distinct poster sessions, in each the posters were up for two days, giving the presenters lots of time for in detail discussions.

Young people were especially encouraged to participate. The conference attracted many scientists across the fields and we were only able to accept about 1/3 of the applicants.

Scientific Content of the Conference

(1 page min.)
- *Summary of the conference sessions focusing on the scientific highlights*
- *Assessment of the results and their potential impact on future research or applications*

Monday 25th	Tuesday 26th	Wednesday 27th	Thursday 28th	Friday 29th
QI I	CQED	QI 2	Atoms+Mols	Ensemble QI
Lukin	Lev	Seidelin	Fattori	Polzik
Garcia-Ripoll	Mekhov	Bruss	Schreck	Giacobino
Coffee Break	Coffee Break	Coffee Break	Coffee Break	Coffee Break
Roos	Brune	Kraus	Meijer	Imamoglu
Sanpera	Blais	Pan	DeMille	Ferlaino/Lopez (H)
Lunch Break and Sports 11:00-15:30 Coffee 15:30-16:00	Lunch Break and Sports 11:00-15:30 Coffee 15:30-16:00	Lunch Break and Sports 11:00-15:30 Coffee 15:30-16:00	Lunch Break and Sports 11:00-15:30 Coffee 15:30-16:00	Lunch Break and Sports 11:10-15:30 Coffee 15:30-16:00
Molecules	Solid state QI		Low-D	Atom-Lattice
Arndt	Törmae (H)	Dürr (H)	Gross	Bloch
Ernst	Aspelmeyer	Fleischhauer(H)	Altmann	Micheli
Rempe	Harmans	Haller (H)	Schumm	Donner
Baranov	Briant	Tuchendler(H)	Dalibard	Jaksch
Dinner break 18:10 – 20:00	Dinner break 18:10 – 20:00	Treutlein(H) Kowalewski(H)	Dinner break 18:10-20:00	Dinner break 18:10 – 20:00
Poster Session I 20:00 – 21:30	Poster Session I 20:00 – 21:30	Conference Dinner 20:00	Poster Session II 20:00 – 21:30	Poster Session II 20:00 – 21:30

Sessions:

Quantum Information QI1, QI2

These two sessions focusing on quantum information (QI) discussed recent advances with photons, atoms, and ions. Topics discussed included teleportation of complex multi particle photon states, one way cluster state quantum computation, long distance quantum cryptography and single photon – single atom physics. A special highlight was the rapid development of ion trap quantum computation and the ways one can use isolated solid state systems for quantum processing. An interesting discussion was brought by the stringent requirements found by the theory of a scalable implementation of a quantum repeater, and the current experiments on quantum memory and quantum transfer between quantum memory nodes.

Ensemble QI

In this session brought together leading groups in quantum physics with atomic ensembles, quantum memory and implementation of a quantum repeater. The speakers represent different approaches ranging from hot atomic cells to ultra cold atomic ensembles and solid state implementations. One of the highlights was a report on the transfer and teleportation of continuous variables quantum states written in an atomic quantum memory.

Solid State QI

This session brought together other approaches in solid state physics where quantum optics phenomena were observed and quantum optic techniques are successfully applied. These range from mechanical systems to quantum dots to isolated impurities in crystals and different types of quantum electronic circuits. Highlight in this session was the rapid progress towards a quantum optics of mechanical resonators. Bringing the “quantum” into mechanics.

Atoms in Lattices

There have been spectacular advances in controlling degenerate quantum gases in “optical lattices”, for bosons, for fermions and mixtures. This session gave an overview of these recent developments and how they might be used for quantum simulating fundamental solid state systems based on the Bose and Fermi Hubbard model.

Low dimensional systems

With the exquisite control over atomic systems, and the ever improving detection and manipulation, this session brought together the physics of small atomic ensembles. Highlights were the squeezing of atomic states, the detailed studies of 1d systems, where both theory and experiment collaborated to find distinct signatures of quantum noise in an interacting many body system, and the detailed analysis of quantum physics in two dimensions.

Atoms + Molecules

These two sessions brought together two different approaches to create ensembles of ultracold molecules: building ultracold molecules from quantum degenerate ensembles of atoms, and decelerating, cooling and trapping molecules from molecular beams. This illustrated the recent year fast progress in the physics of cold molecules. Highlights were the physics of Feshbach resonances and the ability to design the interactions between atoms and build molecules, the study of Efimov states, and coherent matter wave optics with molecular beams.

Cavity Quantum Electro Dynamics

A cooper pair Box interacting with a superconducting strip line cavity id an ideal cavity QED quantum optics system realized in an solid state environment. This is a field with very rapid progress, and the session presented the state of the art and the future trends in this very promising implementation of quantum physics in a solid state environment. This was complemented with methods of Cavity QED to cool molecules and recent advances in controlling and creating quantum states of micro wave radiation in a super conducting cavity.

A special highlight were the hot topic sessions where the contributions were mostly presented by young researchers. At these very new science was discussed, science that was not even envisioned three years ago. Many results had not yet been presented elsewhere before. Similar can be said about the poster sessions. Each poster session lasted for two evenings, there was ample of time and the discussions lasted until midnight and beyond. These poster sessions brought many new contacts and ideas, and we are convinced that there were many new exciting developments which will grow into first grade science results in the near future.

The conference was a beautiful example how in recent years we have seen that the different quantum realizations in the fields of quantum optics and solid state physics have started to move towards each other. On the one hand, quantum optics has been extended to more and more complex systems. On the other hand, solid state systems have entered into the domain of formerly reserved to quantum optics.

In a general discussion one central topic emerged: With the growing connection between traditional quantum optics and solid state physics, more solid state technologies, like nano-fabrication, have become very important to quantum optics. There was a growing demand that the different technologies should be exchanged between the groups so that common problems and advances can be shared.

Forward Look

(1 page min.)
- *Assessment of the results*
- *Contribution to the future direction of the field – identification of issues in the 5-10 years & timeframe*
- *Identification of emerging topics*

Quantum optics is a very active field, which has evolved from the basis of quantum physics of light towards a general science of quantum coherent systems. It is now rooted in photonics, atomic and molecular physics and very recently branched towards solid state physics and real world mechanical systems

The field attracts and is defined by an large number of excellent young scientists with a seemingly unlimited potential for new ideas and an seemingly unlimited set of new tricks to implement them. Many of the experimental results presented at the conference were a few years ago only imagined as gedanken experiments.

Identification of emerging topics

Quantum simulations:

The combination of degenerate quantum gases with optical lattices allows the realization of highly complex but well controlled model systems for solid state physics and offers potential applications in quantum information science. One of the most interesting and promising merging scientific directions are quantum simulators where the tools of quantum optics are used to 'build' well controlled experimental models of theoretical concepts, which are in itself too hard to be solved either by analytic methods or by simulation on classical computers. Ultracold atomic and molecular systems with exquisite control of interaction properties near Feshbach resonances allow the investigation of systems ranging from strongly correlated systems to fundamental few-body systems in molecular or even nuclear physics. Such quantum simulations hold the promise to give us insight into some of the great outstanding problems in solid state physics, like the mechanism behind high-temperature superconductivity, or problems on quantum magnetism.

Besides atoms in optical lattices, quantum simulators based on chains of trapped ions are within reach, and implementations based on chip traps promise scaling to large systems.

Mechanics at the Quantum Level

Remarkable progress was achieved in controlling mechanical systems close to the quantum level. In the future mechanics at the quantum level will develop into a very active subfield of both quantum optics and solid state research. The new techniques to ‚lasercool' external degrees of freedom of mechanical oscillators will build a bridge between different quantum systems.

Solid state based quantum optics

In the realm of solid state physics quantum optical methods are more and more applied. One prominent example presented was the control of single spins systems. This can be extended to possibly larger systems in the near future.

An other important result is that even the icon of quantum optics, the field of cavity QED, has recently found nearly perfect realizations in solid state quantum circuits combining superconducting strip line resonators with the cooper pair box qubit.

In the future we will see even more of quantum optics to move into solid state devices, thereby providing a robust and scalable pathway towards a quantum technology.

Hybrid quantum systems

Presently quantum physics itself is basic research. Quantum physical systems are confined to separate worlds, separated by deserts of classical physics. For quantum physics to emerge from fundamental research one of the main challenges is how to link different quantum systems to each other *and* to preserve the quantum nature also over the link. One has to be able to *quantum interconnect* the different domains. During the conference different new concepts for such interconnects were emerging. In the last years we will see many more such hybrid quantum systems, and they will become a new focus for quantum science research.

▪ Is there a need for a foresight-type initiative?

Business Meeting Outcomes

- *Election of the Organising Committee of the next conference*
- *Identified Topics*
- *Next Steps*

There was a general consensus that the conference series should be continued, and a week in Feb. 2010 was reserved in the Universitätssportzentrum Obergurgl. The team based at the University of Innsbruck was asked to organize the next meeting.

A point of criticism was that due to the ESF organization the meeting became much more expensive than similar previous meetings. In that sense the general way of financing the next meeting was left open.

Atmosphere and Infrastructure

- *The reaction of the participants to the location and the organization, including networking, and any other relevant comments*

The Universitätssportzentrum Obergurgl provided a perfect setting and infrastructure for the Quantum Optics meeting. The atmosphere was very relaxed and collegial. The long time allocated for the poster sessions and the breaks in the afternoon allowed many intense discussions and scientific exchanges.

Confidential Comments

- *Any other comments, not to be included in the published report.*

Date & Author: