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RESEARCH CONFERENCES

ESF-FWF Conference in Partnership with LFUI

Quantum Engineering of States and Devices: Theory and Experiments

5-10 June 2010

Universitätszentrum Obergurgl, Obergurgl, Austria

Chaired:
- Pasquale Sodano, Università di Perugia, Department of Physics, IT
Co-chair:
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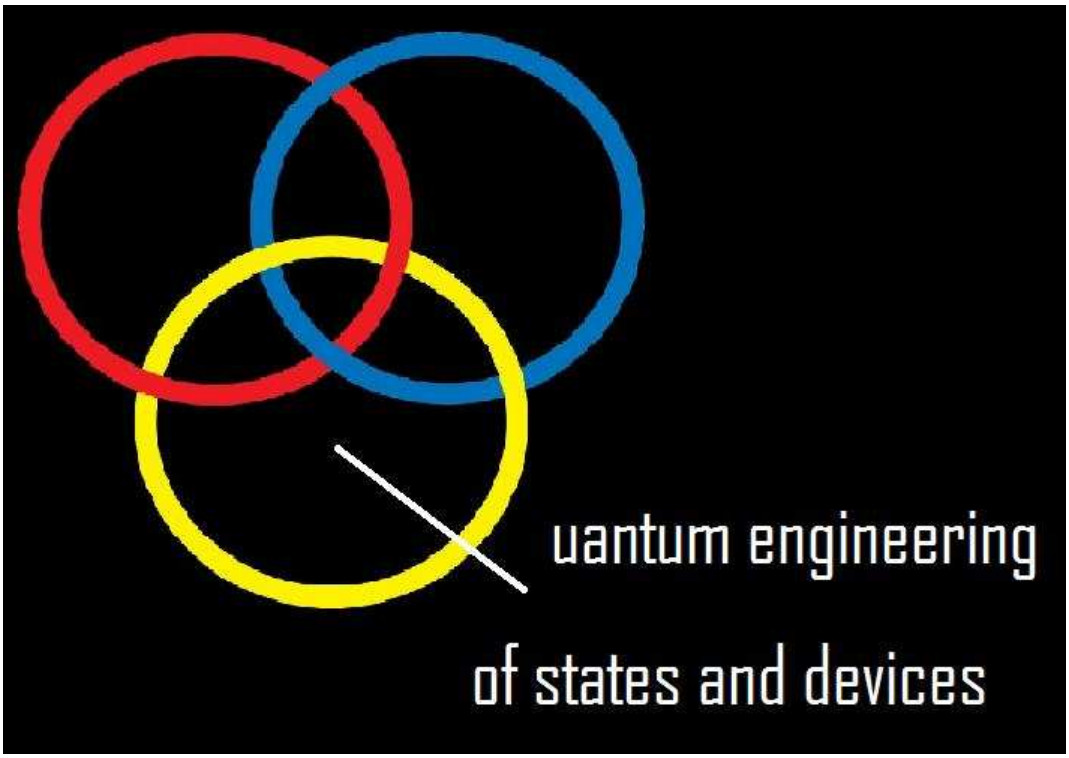

Conference Highlights

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)

Quantum state engineering is by now the subject of an increasing attention. After the realization of experiments where operations with a few qubits were performed in several physical setups, a meeting in which perspectives and problems in this rapidly growing field are discussed was highly desirable. Indeed, the realization of a quantum computer by now become the unifying "hat" for new and remarkable scientific discoveries and technical/methodological advances benefiting many areas of quantum physics and bearing the potential for relevant scientific and technological breakthroughs, which are expected to have an high impact on tomorrow's society. For these reasons, the range of physical systems addressed at the Conference has been purposely very broad reflecting- almost faithfully- the various strategies used so far in pursuing the aim of building a quantum computer. Particular attention has been given to the quantum engineering of Josephson, optical and atomic devices, quantum hybrid systems, trapped ions, biological systems and to results of recent theoretical investigations concerning quantum entanglement, quantum state transfer, topological quantum computation and modern field theories.

The Conference has been focused on recent results concerning the engineering of quantum states realizable in condensed matter systems, with an eye on their potential applications to the solid state realization of qubits and quantum devices. It provided a qualified arena where European, U.S. , Israeli and Canadian physicists from various communities working on solid state physics, quantum field theory and quantum information met to illustrate and debate the huge progresses made in the last years in the creation and control of mesoscopic systems displaying macroscopic quantum coherence.
The contribution of leading experimental physicists in the areas of superconductivity, cold atomic systems, quantum interferometry and metrology, electron gases and quantum dots helped to illustrate- to an audience made essentially by young quantum physicists (both theorists and experimentalists) - the most recent technological advances needed to control and measure quantum coherence in a variety of relevant physical settings.

The conference stimulated new synergies between the various communities to face the challenging task of engineering new quantum settings where quantum information protocols can be implemented.

The overall climate was friendly and stimulating. Despite the intense program there were many informal discussions after dinner and at coffee breaks. Both poster session were highly attended by both lecturers and students. The great contribution given by young physicists was, in my opinion, both enthusiastic and well qualified.

☐ 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)

The programme of the conference consisted of nine topical sessions. Session 1 has been devoted to recent developments in the study of quantum hybrid systems, quantum dots and superconducting devices. The key contributions were delivered by:

Peter Zoller - Institut für Theoretische Physik, AT: *Quantum Hybrid Systems Involving Atomic and Nanomechanical Oscillators*

Vladimir Umansky - Weizmann Institute, IL: *Engineering of Disorder in MBE grown Ultra-High Mobility Two Dimensional Electron System*

Hans Mooij - Delft University of Technology, NL: *Flux qubits: full tunability, qubit-qubit interaction and qubit-resonator coupling*

Alex Retkzer - University of Ulm, DE : *Cooling and transducing using deformation potentials*

Session 2 has been devoted to the characterization and generation of entanglement in condensed matter and spin systems and to their use for quantum metrology. Key speakers included :

Sougato Bose - University College London, UK: *Entanglement across a separation in spin chains: statics & dynamics*

Paolo Zanardi- University of Southern California, Los Angeles, U.S.A.: *Long time dynamics of a quantum quench.*

Roberto Floreanini - INFN, IT: *Using entangled identical particles for sub-shot-noise quantum metrology*

Masudul Haque - Max Planck Institute for Complex Systems, DE : *Hierarchy of edge-locking effects in quantum one-dimensional lattice models*

Vlatko Vedral - University of Oxford, UK: *Entanglement and topological order in self-dual cluster states*

Session 3 has been devoted to new developments of quantum field theories relevant for the analysis of new quantum states of condensed matter systems. Topics concerned non equilibrium transport in quantum dots and coherent phenomena induced by quantum impurities via the Kondo effect. Key speakers included :

Ian Affleck - University of British Columbia, CA: *Non-equilibrium transport through double quantum dot devices: A non-Fermi liquid critical point*

Henrik Johanneson - University of Gothenburg, SE: *Two-impurity Kondo model with spin-orbit interactions*

Lorenzo Campos-Venuti - ISI Foundation, IT: *The fidelity approach, criticality, and boundary-CFT* **.**

Reinhold Egger - Heinrich-Heine-Universität, DE: *Superconducting molecular quantum dots*

Session 4 has been devoted to aspects of quantum physics relevant for biological systems and to recent achievements in the realization of quantum information protocols using trapped Ca+ ions. Key speakers included:

Rainer Blatt - Universtität Innsbruck, AT: *Quantum Information Science with Trapped Ca+ Ions*

Hans Briegel - Institut für Theoretische Physik, AT: *Quantum effects in biological systems*

Session 5 addressed issues relevant for quantum metrology and interferometry. Key speakers included:

Augusto Smerzi - BEC-INFM, IT: *Entanglement and Distinguishability of Quantum States*

Rosario Fazio - Scuola Normale Superiore, IT: *The Quantum optical Josephson interferometer*

Christian Gross- University of Heidelberg, DE: *Nonlinear atom interferometry beyond the standard quantum limit.*

Philipp Treutlein - MPQ/LMU Munich and University of Basel, CH: *Atom-chip-based generation of entanglement for quantum metrology*.

Sessions 6 and 7 addressed recent advances in quantum field theory relevant for topological quantum computation and quantum entanglement in many body systems and cold atoms. Key speakers included:

Ady Stern - Weizmann Institute, IL:*Proposed experiments for observing non-abelian anyons in quantum Hall states*

Lachezar Georgiev - Institute for Nuclear Research and Nuclear Energy, BG: *Thermal broadening of the Coulomb blockade peaks in quantum Hall interferometers*

Giuseppe Mussardo - SISSA, IT : *Non-Abelian Anyons and Topological Quantum Computation*

Jiannis Pachos - *University of Leeds, UK: Anyonic quantum walks: The Drunken Slalom*

Alioscia Hamma - Perimeter Institute for Theoretical Physics, CA: *Topological Renyi Entropy*

Jacopo Catani – LENS, Università di Firenze, IT: *Towards Quantum Magnetism with Ultracold Mixtures of Bosonic Atoms*

Session 8 was devoted to illustrate the nonlocal effects (usable for quantum communication purposes) induced in a solid state system by Majorana fermion bound states: Key speakers included

Roman Jackiw - MIT, US : *Fractional Charge: The Physics of Zero-Energy Modes*

So-Young Pi - Boston University, US: *Quantizing Majorana Fermions in a Superconductor*

Session 9 provided an overview of the most recent advances in the realization of superconducting qubits and to the simulation of quantum systems.

Key speakers included:

Matthew Neeley - University of California, Santa Barbara, US: *Synthesizing complex photon states in superconducting qubits*

Frank Verstraete - University of Vienna, AT: *Quantum simulation and computation using dissipative dynamics*

There were two poster sessions where young scientists presented the results of their research as well as a rather succesfull round table discussion illustrating the interconnection between the efforts of the various communities represented at the Conference.

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*

One may safely say that -amongst its many merits- the quest for a quantum computer brought the research on the foundations of quantum mechanics in close touch with new and exciting quantum technologies bearing the potential for remarkable applications in varied fields ranging from quantum information processing and quantum communication to the engineering of new devices and of "exotic" materials. A key resource of quantum system which reveals crucial for quantum information processing and quantum devices engineering, indeed, is what already Schroedinger -many years ago- defined as ***the trait*** of quantum mechanics: i.e. quantum entanglement.

Two sessions (2 and 5) of the conference were entirely devoted to issues related to the characterization and generation of entanglement in condensed matter and spin systems and to their use in quantum metrology.

One very relevant issue in this context is to find systems exhibiting high and robust entanglement between distant qubits since this is a crucial resource for quantum information processing and for quantum communication tasks: this central issue has been very well highlighted in the invited talk of S. Bose and in the contributed talk of A. Bayat. One relevant observation emerging from these talks is that a Kondo impurity may foster very good (i.e. almost 1) entanglement between very distant qubits. It is pertinent, now, to observe that Kondo impurities are also central for the engineering of quantum transport in quantum dot devices; topic which has been addressed in the invited lectures delivered by I. Affleck, H. Johannesson and R. Egger in Session 3 and in several contributed short communications and posters delivered by participants. The merging of expertises (quantum information theory and condensed matter theory) realized at this conference facilitated many discussions stimulating the emergence of a joint project which aims also at characterizing the " Kondo regime" of a device via pertinent measures of long distance entanglement. This is already a result of the Conference which may lead to the development of a new class of quantum devices where quantum information protocols may be successfully implemented.

Recent results show that long distance entanglement may be induced and observed also in a variety of condensed matter systems if fermionic Majorana midgap states are present: An update of the recent progresses in this new and exciting area has been provided in the invited lectures delivered by R. Jackiw and S. Y. Pi in Session 8. Informal discussions held at the Conference site between a group of participants stimulated the exciting perspective that a quantum wire with Majorana bound states at the edges may scatter incoming electrons so that they will have remarkable interference effects as well as spin entanglement over long distances.

A very relevant aspect of modern research on entanglement addresses the issue of characterizing – via the entanglement- the various orders emerging in condensed matter systems: this topic has been addressed in Session 2 in the invited lecture delivered by V. Vedral and in Sessions 6 and 7 where issues relevant for the quantum entanglement emerging in topologically ordered systems were addressed in the lectures delivered by A. Stern, L. Georgiev, J. Pachos, G. Mussardo, A Hamma and in several contributed short communications and posters delivered by participants. A promising avenue illustrated in some of the lectures and debated in several informal talks at the conference lies on the possibility of providing a full characterization of topologically ordered phases (i. e. phases accessible to matter and quantum devices which cannot be characterized by a local Ginzburg Landau order parameter) via the analysis of the entanglement spectrum and the computation of the Renyi entropy. To fully appreciate the physical

relevance of these approaches suffices to recall that fractional quantum Hall states may be regarded as a prototype of a topologically ordered phase. Measurements of transport in Quantum Hall fluids were reported in the invited lecture delivered by V. Umansky in Session 1. New contacts were established at the Conference site which may foster new collaborations between quantum information theorists and condensed matter physicists with the aim of providing a better characterization of the topological phases of matter.

Non equilibrium quench dynamics (that can be rather easily induced in quantum devices such as quantum dots and Josephson junction arrays by suddenly switching on a control parameter) is, to date, the most promising avenue to generate high –and very robust- entanglement in a condensed matter system. This issue has been addressed in Session 2 by the invited lectures delivered by P. Zanardi and S. Bose and in several posters of the participants. Again the merging of different expertises realized at the conference brought to the forefront the possibility of investigating the peculiarity of quench dynamics in Kondo systems since – as already mentioned above- the latter are very relevant for transport in quantum dots and long distance entanglement. On this (in my opinion, very interesting) topic the Conference provided the ideal setting for many discussions between S. Bose, L. Campos Venuti, P. Zanardi and myself which, hopefully, bear the seed for new and interesting achievements in the near future.

The relationship between entanglement and quantum indistinguishability of particles is a very central issue for quantum metrology and interferometry. This topic has been addressed in the invited lectures delivered by R. Floreanini in Session 2 and- with more emphasis on quantum interferometry- by A. Smerzi ans R. Fazio in Session 5. The experimental signatures of this fundamental relationship have been the object of very recent experiments with cold atomic systems; the results of these experiments, carried by several leading European groups, have been well and extensively summarized in the lectures- delivered in Session 5- of C. Gross and P. Treuthlein.

Other important topics addressed at the Conference were: the realization of qubits in superconducting devices, the use of quantum mechanical systems as quantum simulators, the engineering and the properties of quantum hybrid systems, the realization of quantum information protocols in systems of trapped ions as well as the manifestation of quantum coherence in biological systems .There are several candidates for quantum systems realizing a qubit and/or macroscopic quantum coherence. To date, one of the most promising realizations is based on superconducting devices. A review of these recent developments in superconductivity has been provided in the lecture delivered in Session 1 by H. Mooij and, in session 9, by M. Neeley. The possibility of using quantum systems as quantum mechanical “simulators” has been addressed by J. Catani in Session 6 using cold atomic systems and by F. Verstraete in Session 9 using dissipative quantum mechanics. The potentials of quantum hybrid systems for exciting advances in quantum engineering of devices and new materials were brilliantly reviewed in Session 1 in the invited lecture delivered by P. Zoller. An interesting and stimulating lecture on quantum mechanics of biological systems has been delivered in Session 4 by H. Briegel, while a complete update on the implementation of quantum information protocols with trapped ions has been delivered ,in the same session, by R. Blatt.

To better summarize the various discussions held at the Conference and believed to be relevant for setting new paths for future research and applications in quantum engineering we will edit a special issue of J. Phys. A . expected to come out at the beginning of 2011.

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*

The Conference provided an up to date report on a carefully selected variety of recent results concerning the engineering of quantum states realizable in condensed matter systems and explored their potential applications to the solid state realization of qubits and quantum devices. The meeting of different communities working with the "common aims" of realizing a quantum computer and of finding condensed matter systems usable for the implementation of quantum protocols revealed itself very beneficial for pointing out future directions in a field which is intrinsically multidisciplinary. In the previous sections of this report I already mentioned various areas where new collaborations stimulated by this Conference may arise. In the following I will report in same detail on a new direction of future research which rose from the meeting at the Conference site of experts in condensed matter systems (mainly working on quantum dots and Kondo effect) and quantum information theory.
Through several informal discussions commenting on the lectures delivered in different sessions of the conference it emerged that quantum impurities may soon become a major resource for the engineering of new quantum devices. We come also to the realization that an understanding of the role of impurities is crucial for controlling a variety of new quantum behaviors accessible to quantum systems. We strongly felt that there is by now growing evidence that, by judiciously engineering the coupling of an impurity to its environment, one can:

A) Generate long distance correlations (entanglement) and improve the efficiency of quantum communication ;
B) Set new stable phases in quantum systems ;
C) Facilitate enhanced responses to external perturbations in solid state devices;
D) Induce the emergence of new phases in cold atomic systems;
E) Engineer devices useful for topological quantum computation;
F) Apply to the engineering of solid state devices field theoretical methods recently developed in string and boundary conformal field theories.

The control of quantum impurities is already very important in Josephson devices and ultra-cold atomic systems confined by optical lattices. Introducing quantum anti-dots in FQH states also provides relevant examples of device candidates for the implementation of topological quantum information processing. Quantum Impurities are also expected to be relevant for quantum state transfer and quantum communication as well as for inducing enhanced responses to external perturbations, as evidenced in the talks by Bose, Bayat and Johannesson delivered at the Conference. In many instances methods from string and boundary field theories account for the explanation of these phenomena, as evidenced in the talks by I. Affleck, L. Campos Venuti and D. Giuliano. The activity we plan to launch on this topic is aimed at creating a framework where all the different expertise needed to understand items A-F may successfully merge.

It is foreseeable that gathering a qualified group of European physicists and quantum information theorists, well connected to U.S., Canadian and Israeli colleagues, may lead to the development of a very new branch of quantum engineering where world excellence may be achieved within Europe. Given the fact that, in order to achieve remarkable results in this area, one needs inputs from various communities the Conference may be regarded also as a first step to create a remarkable opportunity for the education of young physicists in an area in which complementary skills are needed.

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

Yes. There is interest from a number of conference participants to use ESF instruments to foster and strengthen the new possible collaborations envisaged at the Conference; unfortunately, ESF decided to postpone for unknown time the launching of the call for Research Networking Programmes (RNPs), which might have been very adequate for establishing a stable network on some of the topics of this conference: the one described in the previous section being just an example of the many new potential collaborations . Nonetheless, a limited number of the conference participants might find it interesting to participate in the newly launched RNP POLATOM (Common perspectives for cold atoms, semiconductor polaritons and nanoscience). We have been informed that a new Forward Look on future perspectives of quantum information is expected to be launched this autumn; this might involve many participants of the consortium of this conference in the strategic foresight action. We plan to apply to this program as well as to the COST action whose next collection date has been fixed for September 24 2010.

Atmosphere and Infrastructure

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

The venue of the Conference facilitated many discussions between lecturers and participants stimulating the creation of new collaborations leading – in some instances- to the formulation of new interdisciplinary research projects to be submitted in future calls for networks. The atmosphere in Obergurgl was very friendly and the host structure had the infrastructures (common rooms, study rooms, dining hall for instance) which facilitated the many informal exchanges between the participants to the conference. The very comfortable rooms, the easy internet access, the beauty of the surroundings contributed to make the participants feel happy and, thus, much more outgoing. The possibility offered by the center to have take-way lunch packs offered to groups of participants to join for excursions in the Alps or to participate to rather adventurous and exciting river rafting trips. The on site support provided by the centre' s staff for the various planned activities of the Conference was always very prompt and of outstanding quality.

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