



ESF Exploratory Workshop

## Quantum Technologies: Hybrid Emitter-Solid State Systems

21-24 September 2014

ISIS, Strasbourg, France

Chair: **Prof. Guido Pupillo**

ISIS-IPCMS, Université de Strasbourg and  
CNRS, FR

Co-Chairs: **Dr. Claudiu Genes**

Institute für Theoretische Physik, Universität  
Innsbruck, AT

**Prof. Philipp Treutlein**

Dept. of Physics, University of Basel, CH

**With the support of:**



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# SCIENTIFIC REPORT

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## 1. Executive summary

The aim of the workshop “Quantum Technologies: hybrid emitters – solid state systems” was to bring together leading scientists from diverse fields such as optomechanics, cold atom/molecule physics, ion trap physics, in order to contribute to developing new ideas and approaches for the realization of coherent, hybrid mechanical interfaces, and to identify new research directions and applications of these novel systems.

The interfacing of quantum emitters with a mesoscopic mechanical device will have profound impact in basic science as we aim at an unprecedented level of control of the mechanical response in order to allow for the operation – cooling, state preparation, readout – of mechanical oscillators in the quantum regime. Moreover, such systems can provide a deeper understanding of the interplay between macroscopic phenomena and genuinely quantum-mechanical features of many-body systems. The projected fallouts in technology are numerous as hybrid optomechanical devices can potentially act as beyond-state-of-the-art precision sensors for metrology applications. They are also bound to lead to several breakthroughs in applications for Information and Communication Technologies, for example in the areas of energy consumption and data and operation integrity.

The workshop “QThYES“ has provided talks from some of the world’s leading experts, as well as from young very promising scientists in the fields of micro, nano- and pico-optomechanical engineering. The high quality of the involved scientists was reflected in a very high quality of the talks. The latter have been followed by intense and friendly scientific debates at the end of almost each talk. Thanks to the high level of research presented at talks and at the poster sessions, the atmosphere of the workshop was extremely stimulating. We got feedback from many participants, expressing their appreciation for the quality of the presentations and the general format of the workshop, which included long lunch breaks - perfect for discussions. Poster sessions have been very successful, lasting long after the allocated hours. The long lunch breaks have been ideal times for people to do networking and start collaborations. We are aware of at least a few collaborative research initiatives which have started at the conference among participants with the aim to apply to collaborative grant initiatives, such as within Horizon2020.

There have been several scientific highlights worthy of notice. Examples are the development of new experimental techniques for interfacing nano-mechanical systems with nitrogen vacancies (NV) centers in diamond, experimental evidence of atomic control of mechanical motion in macroscopic resonators or proofs of efficient optomechanical coupling between graphene resonators and superconducting cavities. The initial goal of the workshop to provide alternative views on similar topics has been met, as competing experimental groups have reported state-of-the-art results and compared them against expectations set by the participating theorists.

Due to the relative novelty and importance of this field of research, several of the topics touched in this conference are bound to provide exciting, fundamental, breakthroughs in the next 5 to 10 years. Very exciting new research directions may come from, e.g., the possibility to assist mechanical cooling and quantum state control and generation via indirect manipulation of atomic ensembles, ion crystals or embedded vacancies/quantum dots. This direction provides an alternative to traditional optomechanics where the typically low photon-phonon interactions hinders progress towards accessing the full quantum mechanical regime.

Overall, the workshop “QThYES” was a resounding success. It is the impression of most of the participants that coordinated actions towards further strengthening ties within this remarkably innovative, diverse, productive community would be highly desirable, both at the international and European levels. If at all possible, these actions should encompass the organization of further conferences in the field, and the organization of large- and medium-scale collaborative grant initiatives at the European level.

## **2. Scientific content of the event**

The conference sessions have been characterized by the remarkably high quality of talks, which mirrors the remarkably high quality of the speakers. Here is a breakdown of the conference, session by session, focusing on a few (of the many) highlights:

### **Session 1**

The opening session was mainly devoted to overview talks by leading senior scientists in the field of optomechanics. Eugene Polzik (QUANTOP, DK), has presented new promising experimental results that see extraordinary concepts such as the monitoring of trajectories without quantum uncertainties in hybrid atomic-mechanical resonator systems.

In the next talk, Helmut Ritsch (Innsbruck), a leading scientist that has pioneered the field of cavity optomechanics with atoms, gave an overview talk on many-particle dynamics under the influence of time-dependent optical potentials. The following discussion resulted in the outlining of exciting prospects of applications of these concepts to optomechanics with resonators at larger mass scaled where similar effects are expected.

The session was closed by an experimental talk by Tobias Kampschulte (Basel, CH) showing amazing progress in the coupling of membranes to laser cooled atomic ensembles and the prospects for ground state cooling.

### **Session 2**

This session was almost entirely devoted to theoretical and experimental progress in the mechanical coupling via nitrogen vacancies in diamond spins. Theoretical predictions and techniques have been introduced by Peter Rabl (Vienna) and experimental progress has been addressed by competing (and also collaborating) experiments conducted in the groups of Ania Bleszynski-Jayich (Santa Barbara), Patrick Maletinsky (Basel) and O. Arcizet (Grenoble).

### **Session 3**

In this session prospects for extensions to multielement optomechanics have been presented, with theoretical concepts and applications on strong coupling via membrane arrays introduced by Andre Xuereb (Malta). This promising route could be pursued on diverse platforms such as those described experimentally by M. Sillanpää (Aalto) and Gary Steele (Delft) in the context of superconducting cavities or by Aurelien Dantan (Aarhus) on membrane stacks. Possible optomechanical schemes either direct (with motional modes of ion crystals) or indirect or ions are coupled to vibrating membranes have been put forward by the Aarhus group as well.

The JILA group contributed breakthrough results on frequency conversion and quantum limited cooling with membranes in cavity setups and suggested possible extension to multiple membrane systems currently under preliminary investigations.

### **Session 4**

In this session, exciting prospects for bridging different approaches towards optomechanics were presented, as a new vision was proposed by the leading physical chemist Thomas Ebbesen (Strasbourg), based on a molecular system where mapping of molecular vibrations onto internal degrees of freedom have been shown to lead to great enhancement in optomechanical coupling. This view has been contrasted to a more physics-based approach by Tobias Kippenberg (Lausanne), who has shown new experimental results towards the application of feedback techniques of thermal decoherence rates.

The session continued with interesting theoretical prospects proposed by Giovanna Morigi (Saarbrücken) to interface single photon pulses with superconducting qubits and was concluded by experimental talks by Ivan Favero (Paris) on coupling of gallium arsenide optomechanical disk resonators and by Andrew Geraci (Nevada) who advanced an alternative technique for coupling atomic ensembles to mechanical resonators that could allow in principle single spin sensitivity.

## **Session 5**

Jean Philippe Poizat (Grenoble) opened this session with a presentation on current experimental efforts towards mechanical control via quantum dots where coupling occurs via strain. In a logical continuation, the competing experiment of Martino Poggio (Basel) provided similar breakthrough results based on experiments involving a fully assembled nanowire. Discussions on possible collaborations naturally followed.

Theoretical analyses and predictions for experiments presented in Session 1 have been presented by Berit Vogell (Innsbruck) who has modelled the atom-membrane interaction occurring in experiments in Basel and proposed future setup modifications, leading to fruitful discussions.

The session was concluded by two energetic talks, one on the experimental side where Jeff Thompson (Harvard) has presented progress in the group at Harvard towards nanoscale quantum optics with cold atoms in cavity QED and prospects for generation of quantum technologies. Cristiano Ciuti (Paris) gave a theorist's perspective on hybrid systems, where the strong coupling regime of light-matter interactions opens the way towards polariton-mediated mechanical control.

## **Session 6**

David Vitali (Camerino) presented a nice example of perfect collaboration between theory and experiment as he is leading an optomechanics group containing both theorists and experimentalists, where ideas are immediately put in practice in already existing local setups. His talk was followed by a theoretical presentation by Klemens Hammerer (Hannover) who introduced a novel idea of continuous monitoring of hybrid systems, departing from typical conditional dynamics treatments of quantum dynamics.

Witlief Wieczorek (Vienna) presented a very interesting approach to experimentally detect non-classical states via Kalman filtering where methods proposed by the group of Hammerer were successfully experimentally tested.

The session was closed by the talk of Yutako Shikano (Okazaki) who introduced alternative systems to test optomechanical concepts at the micro-scale, specifically focusing on the realization of a quantum rotor model in linear Paul traps.

Plenary discussions followed, where the ESF officer addressed the participants asking for general statements for the future of quantum based hybrid technologies. High-spirited constructive discussions followed, where everybody's vision on the long term goals of these technologies were outlined. These discussions extended well into the poster session.

## **3. Assessment of the results, contribution to the future direction of the field, outcome**

The atmosphere of the workshop was extremely stimulating, thanks to the very high level of the talks and of research presented at the poster sessions. We had feedback from many participants, who have confirmed their appreciation of the quality of the presentations and the general format of the conference, which included long lunch breaks (perfect for discussions). The atmosphere was also very informal, so that many discussions which were generated at the talks continued during the long lunch breaks and at/after poster sessions.

The breakthroughs, both experimental and theoretical, presented at the workshop have been numerous. Many of them have been outlined above. Here is a list of the major topics for future research and areas of potential breakthroughs that have come out as a result of the discussions, including one initiated by the ESF officer, who was a very constructive partner for discussions.

Future projected research directions and breakthroughs:

- Efficient conversion between electronic and optical signals at the level of single quanta

- Chemically selective single nuclear spin detection with nanometer resolution by MRFM techniques
- Displacement measurements at the Heisenberg limit using Einstein-Podolsky-Rosen entanglement
- Micro-macro entanglement (Schroedinger's cat) and tests of the limits of quantum mechanics

We are aware of at least a few collaborative research initiative which have started at the conference among participants (some of them with the intent to apply to collaborative grant initiatives, such as Horizon2020).

#### 4. Final programme

##### 21/09 Sunday, 2014

Evening *Arrival*

##### 22/09 Monday, 2014

- |             |   |
|-------------|---|
| 09.00-09.30 | <b>Welcome by Convenors</b>   |
| 09.30-09.30 | <b>Presentation of the European Science Foundation (ESF)</b><br>Scientific Review Group for Physical and Engineering Sciences   |
| 09.30-10.00 | <b>Presentation 1 "Experiments on trajectories without quantum uncertainties"</b><br><b>E. Polzik</b> (QUANTOP, Niels-Bohr Institute, Copenhagen, Denmark)                      |
| 10.00-10.30 | <b>Presentation 3 "Light induced interaction, self-ordering and collective dynamics of point scatterers in 1D"</b><br><b>H. Ritsch</b> (Univ. of Innsbruck, Innsbruck, Austria) |
| 10.30-11.30 | <i>Coffee / Tea Break</i>   |
| 11.30-12.00 | <b>Presentation 5 "Sympathetic cooling of a membrane oscillator in a hybrid mechanical-atomic system"</b><br><b>T. Kampschulte</b> (Univ. of Basel, Basel, Switzerland)         |
| 12.00-12.30 | <b>Presentation 4 "*****"</b><br><b>M. Vengalattore</b> (Cornell Univ., Ithaca, USA)  |
| 12.30-14.30 | <i>Lunch</i>  |
| 14.30-15.00 | <b>Presentation 1 "NV phonon interactions in diamond"</b><br><b>P. Rabl</b> (Vienna University of Technology, Vienna, Austria)  |
| 15.00-15.30 | <b>Presentation 5 "Strain-mediated mechanical coupling to diamond spins"</b><br><b>A. Bleszynski Jayich</b> (Yale Univ., New Haven, USA)  |
| 15.30-16.30 | <i>Coffee / tea break</i>   |
| 16.30-17.00 | <b>Presentation 3 "Hybrid spin-optomechanics with strain coupled NV centers"</b><br><b>P. Maletinsky</b> (Univ. of Basel, Basel, Switzerland)                                   |

- 17.00-17.30 **Presentation 4 “Hybrid spino-nanomechanical system”**  
**O. Arcizet** (Univ. Joseph Fourier, Grenoble, France)
- 17.30-18.00 **Presentation 4 “Dynamics of strongly coupled nanomechanical resonator modes”**  
**E. Weig** (Univ. of Konstanz, Konstanz, Germany)
- 18.00-19.00 **Poster session 1**

**23/09 Tuesday, 2014**

- 09.00-12.00 Morning Session: Towards multielement optomechanics**
- 09.00-09.30 **Presentation 3 “OM at microwave frequencies: mechanical resonators coupled to microwave cavities and superconducting qubits”**  
**M. Sillanpää** (Aalto Univ., Espoo, Finland)
- 09.30-10.00 **Presentation 2 “Reconfigurable long-range phonon dynamics in optomechanical arrays”**  
**A. Xuereb** (University of Malta, Msida, Malta)
- 10.00-10.30 **Presentation 1 “OM coupling between a graphene resonator and a superconducting microwave cavity”**  
**G. Steele** (Delft Univ. of Technology, Delft, The Netherlands)
- 10.30-11.30 *Coffee / Tea Break*
- 11.30-12.00 **Presentation 3 “Frequency conversion and quantum backaction limited cooling in a membrane optomechanical cavity”**  
**T. Purdy** (JILA, Boulder, USA)
- 12.00-12.30 **Presentation 2 “Optomechanics with ion crystals and flexible membranes”**  
**A. Dantan** (University of Aarhus, Aarhus, Denmark)
- 12.00-14.30 *Lunch*
- 14.30-15.00 **Presentation 5 “Coherent coupling of molecular resonators with a micro-cavity mode”**  
**T. Ebbesen** (ISIS, Univ. Strasbourg and CNRS, Strasbourg, France)
- 15.00-15.30 **Presentation 4 “\*\*\*\*\*”**  
**T. Kippenberg** (Univ. of Saarlandes, Saarbrücken, Germany)
- 15.30-16.30 *Coffee / Tea Break*
- 16.30-17.00 **Presentation 4 “Interfacing Superconducting Qubits and Telecom Photons”**  
**G. Morigi** (Univ. of Saarlandes, Saarbrücken, Germany)
- 17.00-17.30 **Presentation 1 “High frequency gallium-arsenide optomechanical systems”**  
**I. Favero** (Univ. Paris Diderot and CNRS, Paris, France)

- 17.30-18.00 **Presentation 3 “Coupling cold atoms to mechanical resonators via spin”**  
**A. Geraci** (Univ. of Nevada, Reno, USA)
- 19.00-22.00 **Conference dinner**

#### **24/09 Wednesday, 2014**

- 09.00-09.30 **Presentation 4 “Strain-mediated coupling in a quantum dot-mechanical oscillator hybrid system”**  
**J-Ph. Poizat** (Univ. Joseph Fourier, Grenoble, France)
- 09.30-10.00 **Presentation 3 “Quantum dot OM in a fully self-assembled nanowire”**  
**M. Poggio** (Univ. of Basel, Basel, Switzerland)
- 10.00-10.30 **Presentation 4 “Cavity-enhanced long-distance coupling of a mechanical resonator to an atomic ensemble”**  
**B. Vogell** (IQOQI, Innsbruck, Austria)
- 10.30-11.30 *Coffee / Tea Break*
- 11.30-12.00 **Presentation 2 “Efficient fiber-optical interface for nanophotonic devices”**  
**J. Thompson** (Harvard Univ., Cambridge, USA)
- 12.00-12.30 **Presentation 1 “Hybridizing cavity QED and optomechanics”**  
**C. Ciuti** (Univ. Paris Diderot and CNRS, Paris, France)
- 12.30-14.30 *Lunch*
- 14.30-15.00 **Presentation 2 “Certified entanglement between distant microwave fields with opto-electro-mechanical systems”**  
**D. Vitali** (Univ. of Camerino, Camerino, Italy)
- 15.00-15.30 **Presentation 2 “Hybrid quantum dynamics under continuous measurement”**  
**K. Hammerer** (Leibniz Univ., Hannover, Germany)
- 15.30-16.30 *Coffee / tea break*
- 16.30-17.00 **Presentation 2 “Of materials and methods: tensile-strained InGaP membranes and state estimation via Kalman filtering for cavity optomechanics”**  
**W. Wieczorek** (Univ. of Vienna, Vienna, Austria)
- 17.00-17.30 **Presentation 5 “Observation of Aharonov-Bohm effect with quantum tunneling”**  
**Y. Shikano** (IMS, Okazaki, Japan)
- 17.30-18.00 **Plenary discussions on follow up research activities and collaborative actions**
- 18.00-19.00 **Poster session 2**

#### **25/09 Thursday, 2014**

Morning *Departure*

**5. Final list of participants** (name and affiliation is sufficient; the detailed list should be updated on-line directly)

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**6. Statistical information on participants** (age bracket, countries of origin, M/F repartition, etc.) The statistics to be provided under section 6 can also include repartition by scientific specialty if relevant.

**Age bracket:** 28 to 60 (mean approx. 40)

**Countries of origin:**

France	7
Switzerland	6
Austria	5
USA	5
Germany	3
Denmark	2
Finland	1
Italy	1
Japan	1
Malta	1
Netherland	1

**F/M ratio:** 15%. However small, this is significantly higher than the overall percentage of female PIs in the field.