AKTION Österreich – Tschechische Republik **n. 76p14**

Generation of nonclassical states of light and motion

Final report

We present the final status of progress in common research, collaboration and results achieved within the one year bilateral scientific project between the experimental quantum optics research teams from Palacký University in Olomouc and Leopold-Franzens University of Innsbruck. The presented report is divided into several chapters which summarize the accomplishments in both formal and scientific goals of the project.

Realized activities

(chronologically)

-November 2016

Postgraduate student Petr Obšil stayed for one month at the Institute for Experimental Physics in Innsbruck and contributed to several crucial technical tasks in the laboratory focused on quantum optics experiments with trapped Barium ions. Together with PhD student Gabriel Araneda and university assistant Dr. Yves Colombe, they have worked on rebuilding and improving frequency locking schemes of several excitation lasers. They have further worked on implementation of the electromagnetically-induced-transparency laser cooling technique with the aim of shortening the ground-state cooling times of trapped barium ions, which is a crucial prerequisite for planned experiments sensitive to phase coherence of emitted fluorescence photons. Within his stay, Petr presented recent results from Olomouc's ion trapping experiment in a talk entitled "Nonclassical light from large ensembles of trapped ions".

-February 2017

Postdoctoral researcher Lukáš Slodička visited the Institute for Experimental Physics for one week. This visit has been focused on planning of new experiments realized both in the Barium laboratory at the Institute of Experimental physics in Innsbruck and Czech ion trapping laboratory in Brno. In addition, finalization of our common manuscript entitled "Interference of single photons emitted from entangled atoms in free space" have been discussed, especially application possibilities of the realized scheme for sensing and detection of quantum entanglement from spatially distant ions. Dr. Slodička was introduced into new capabilities of developed camera detection setup in Barium laboratory, enabling unprecedentedly fast tracking of ion's position. This has further constituted a basis for our experimental proposal of direct detection of ion's motional state. The visit resulted also in a preliminary proposal for a new versatile miniature ion trapping apparatus, which has been submitted as a common project within the QuantERA 2017 call, together with Innsbruck colleagues Dr. Thomas Monz and Philipp Schindler. Possible further enhancements of the laser locking scheme in Olomouc's ion trapping experiment have been discussed with several other members of Prof. Rainer Blatt's group, particularly experimental methods of overcoming reference frequency comb offset noise using feed-forward techniques.

-May 2017

Senior researcher Dr. Yves Colombe visited the Department of Optics of Palacky University in Olomouc for three days. Together with several colleagues from Olomouc's quantum optics laboratory, he discussed several experimental research directions of Olomouc's group, in particular the generation of nonclassical light in warm atomic ensembles and the realization of photonic linear optical quantum gates. The main part of his visit was focused on further discussions of possible direct observation of nonclassical properties of trapped Barium ion –

mechanical oscillator with Prof. Radim Filip and Dr. Lukas Slodicka. Within his stay, Dr. Colombe gave a talk entitled "Recent results from the Barium ion experiment in Innsbruck".

-June 2017
Prof. Radim Filip together with postgraduate student Lukáš Lachman and Dr. Lukáš Slodička visited the Institute of Experimental Physics in Innsbruck. Prof. Filip and Mag. Lachman stayed for three days, Dr. Slodička visited for one week.
The visit has been mainly focused on theoretical concepts underlying possibilities of measurement of nonclassical properties of light emitted from trapped ions, especially measurement of quantum non-Gaussianity of light emitted from two and more ions. The particularly fruitful discussions about direct observation of squashing of ion's motional quadratures using fast camera detection led to immediate setting and observations of the averaged coherent ion's motion in the laboratory with colleague Mag. Gabriel Araneda. These measurements continued later this summer by setting up the camera acquisition in an experimental pulse sequence for directly resolving the ion's position with a time resolution much smaller than the period of its coherent oscillation. This constitutes a crucial step towards experiments in which metrologically attractive squashing of the ion's motional quadratures becomes directly observable without need for usual spectroscopic techniques. The visit in Innsbruck included also several detailed lab-tours and discussions related to nonlinear optical conversion at single photon level (Dr. Ben Lanyon) and further planning of the novel versatile apparatus with possibility of good optical access (Dr. Philipp Schindler and Dr. Thomas Monz).

-August 2017
Postgraduate student Mag. Gabriel Araneda visited the Department of Optics in Olomouc and our ion trapping experiment located at the Institute of Scientific Instruments of Czech academy of Sciences in Brno for five days. The main part of the visit has been focused on observation of the phase interference of light scattered from several ions in the direction coinciding with the axial direction of the trap. Together with local PhD students (Mag. Petr Obšil and Mag. Adam Lešundák), we were able to observe first interference signal from two and three ion strings. Although these results are conceptually similar to previously realized Young's type interference experiments with trapped ions in Boulder and Mainz, the realized approach of coupling ions along the elongated crystal symmetry axis enables efficient collection and indistinguishability of fluorescence from much larger ion ensembles and thus allows the efficient optical generation of multi-ion entanglement, observation of enhanced squeezing of resonance fluorescence, or studies of bare superradiance effects with well localized large samples of atomic particles. Mag. Araneda has been introduced to the novel laser locking scheme corresponding to frequency stabilization of five visible spectrum diode lasers to single fiber frequency comb after its frequency doubling and broadening. Further improvements of long-term laser stabilities limited by the stability of supercontinuum spectrum as well as the comparison of the low-finesse cavity to fiber spool pre-stabilization techniques have been discussed and analyzed.

In addition to the listed particular activities, the Innsbruck and Olomouc project participants have been continuously collaborating by exchange of new experimental ideas, common writing of manuscript, or searching for particular solutions to new experimental challenges. Among countless discussions it is worth mentioning the contributions to estimation of vacuum conditions in Olomouc's trapped ion setup by Dr. Yves Colombe or discussions about the new experimental apparatus in the Barium lab with high numerical aperture spherical mirror.

Summary of achieved results

The main results of the project can be conveniently divided into two categories, namely technological improvements and scientific advances. The mutual collaboration has strongly contributed to realization of the **several narrow-band laser setups in Innsbruck laboratory** as well as the **completion of the laser frequency stabilization scheme in Czech** ion trapping setup. We have together planned and **have begun realizations of two complementary experiments** with prospects of studying the **nonclassical properties of ion's motion using fast camera detection** (Innsbruck) and **phase properties of light scattered from large ion crystals** (Olomouc). Although these experiments are not yet in the final stage due to their complex nature, the preliminary measurements of coherent ion motion and phase interference of photons emitted in the trap axial direction promise their successful outcome. In addition to these newly achieved results, we **have written and submitted for publication a common manuscript presenting optical generation and estimation of entanglement of remote ions**, presenting results achieved prior the period of this project. Together with additional three other European teams, we have prepared and **submitted a collaborative funding proposal for realization of industry based versatile ion trapping apparatus in Europe** (QuantERA Network).

Collaboration summary

The project has led to further strengthening of the previous collaboration between Olomouc and Innsbruck ion trapping teams mainly by enabling number of fruitful discussions, planning, and common laboratory research within several short term visits. Both teams could together achieve substantial progress in experimental setups focused on the direct observation of nonclassicality of motion (Innsbruck) and phase properties of scattered light from trapped ion strings (Olomouc). The scientific expertise required for the above mentioned results were to large extent complementary and both teams have thus strongly benefited from the intensified collaboration. The preliminary experimental results promise important contribution to understanding of the effects related to light matter interaction at single atom - single photon level and development of novel detection methods of motional states of atomic particles.

Dr. Lukáš Slodička

26. 9. 2017

Lukáš Slodička

Dr. Yves Colombe

25.09.2017

Appendix A
List of participants
(alphabetically)

Students

Mag. Gabriel Araneda
Mgr. Lukáš Lachman
Ing. Petr Obšil

Scientists

Dr. Yves Colombe
Dr. Radim Filip
Dr. Lukáš Slodička