Control of Quantum Dynamics of Atoms, Molecules and Ensembles by Light

Kempinski Hotel Grand Arena, Bansko, Bulgaria, March 12 – 16, 2018

CAMEL XIV

Fourteenth International Workshop

BOOK OF ABSTRACTS

Edited by

Svetoslav Ivanov and Nikolay Vitanov

Supported by

Bulgarian NSF Grant DN 18/14

Local Organizing Committee

Nikolay Vitanov (chairman), Genko Genov
Andon Rangelov, Svetoslav Ivanov
Emiliya Dimova, Hristina Hristova
Kaloyan Zlatanov, Lachezar Simeonov
Peter Ivanov, Elena Stoyanova
Boyan Torosov

Quantum Optics and Quantum Information Group
Theoretical Physics Division
Department of Physics
Sofia University "St. Kliment Ohridski"
5 James Bourchier Blvd, 1164 Sofia, Bulgaria
http://camel14.quantum-bg.org

Contents

List of Participants

Nati Aharon (Jerusalem)
Tommaso Calarco (Ulm)
Emiliya Dimova (Sofia)
Tom Dowdall (Cork)
Michael Drewsen (Aarhus)
Barry Garraway (Sussex)
Wojciech Gawlik (Krakow)
Genko Genov (Darmstadt)
Roberto Grimaudo (Palermo)
Stephane Guerin (Dijon)
Georg Heinze (Barcelona)
Markus Hennrich (Stockholm)
Winfried Hensinger (Sussex)
Hristina Hristova (Sofia)
Peter Ivanov (Sofia)
Svetoslav Ivanov (Sofia)
Matthias Keller (Sussex)
Martina Knoop (Marseille)
Axel Kuhn (Oxford)
Sabrina Maniscalco (Turku)
Antonino Messina (Palermo)
Germano Montemezzani (Metz)
Sorin Paraoanu (Aalto)
Anna-Greta Paschke (Hannover)
Jyrki Piilo (Turku)
Ana Predojevic (Stockholm)
Andon Rangelov (Sofia)
Lachezar Simeonov (Sofia)
Elena Stoyanova (Sofia)
Haim Suchowski (Tel Aviv)
Boyan Torosov (Sofia)
Nikolay Vitanov (Sofia)
Thomas Walther (Darmstadt)
Christof Wunderlich (Siegen)
Kaloyan Zlatanov (Darmstadt)

Bulgaria	9	Denmark	1	Finland	3
France	3	Germany	6	Ireland	1
Israel	2	Italy	2	Poland	1
Spain	1	Sweden	2	United Kingdom	4

Programme

Monday, March 12

Lunch Session chaired by **Jyrki Piilo**

13:30-14:10 **Sabrina Maniscalco**, *Bosonic Complex Quantum Networks: What, when and why*

14:10-14:50 **Barry Garraway**, *Decay of quantum systems analysed with pseudo-modes of reservoir structures*

14:50-15:20 **Coffee break**

Afternoon Session chaired by **Christof Wunderlich**

15:20-16:00 **Markus Hennrich**, *Interacting Rydberg ions*

16:00-16:40 **Michael Drewsen**, *Coherent internal state manipulation of single atomic and molecular ions by optical frequency combs*

16:40-17:10 **Coffee break**

Evening Session chaired by **Michael Drewsen**

17:10-17:50 **Ana Predojevic**, *Solid State Source of Photon Triplets*

17:50-18:20 **Anna-Greta Paschke**, *Recent progress towards quantum logic inspired cooling and readout techniques for single (anti-)protons*

18:20-18:40 **Roberto Grimaudo**, *Exactly Solvable Generalized Rabi Systems*

Tuesday, March 13

Lunch Session chaired by **Sabrina Maniscalco**

13:30-14:10 **Tommaso Calarco**, *Quantum technologies: closing the control loop*

14:10-14:50 **Jyrki Piilo**, *Fully controlled dephasing dynamics and synthetic spectral densities*

14:50-15:20 **Coffee break**

Afternoon Session chaired by **Markus Hennrich**

15:20-16:00 **Christof Wunderlich**, *Speeding-up the Decision Making of a Learning Agent Using an Ion Trap Quantum Processor*

16:00-16:40 **Winfried Hensinger**, *Constructing a multi-module trapped-ion quantum computer prototype*

16:40-17:10 **Coffee break**

Evening Session chaired by **Thomas Walther**

17:10-17:50 **Georg Heinze**, *Towards Entanglement between Disparate Matter Quantum Nodes*

17:50-18:20 **Genko Genov**, *Experimental Demonstration of Composite Stimulated Raman Adiabatic Passage*

18:20-18:40 **Tommaso Calarco**, *Flagship on Quantum Technologies*

20:00 **Conference dinner**

Wednesday, March 14

Lunch Session chaired by **Matthias Keller**

13:30-14:10 **Thomas Walther**, *Fiber Amplifiers and their Applications in Doppler Cooling and Quantum Key Distribution*

14:10-14:50 **Axel Kuhn**, *Elements of a Cavity-Based Atom-Atom Entangler*

14:50-15:20 **Coffee break**

Afternoon Session chaired by **Axel Kuhn**

15:20-16:00 **Wojciech Gawlik**, *Coherence and nonlinear spectroscopy in NV diamond*

16:00-16:40 **Matthias Keller**, *Ion-Photon Interfaces for Quantum Networks*

16:40-17:10 **Coffee break**

Evening Session chaired by **Germano Montemezzani**

17:10-17:50 **Sorin Paraoanu**, *Superadiabatic population transfer by loop driving and synthetic gauges in a superconducting circuit*

17:50-18:20 **Boyan Torosov**, *Arbitrarily accurate twin composite pulse sequences*

18:20-18:40 **Kaloyan Zlatanov**, *Optically stimulated third harmonic generation*

18:40-19:00 **Hristina Hristova**, *Adiabatic three-waveguide coupler*

Thursday, March 15

Lunch Session chaired by **Barry Garraway**

13:30-14:10 **Stephane Guerin**, *Robust control of linear and non-linear quantum systems by shaped pulses*

14:10-14:50 **Martina Knoop**, *Three-photon precision spectroscopy of a large ion cloud*

14:50-15:20 **Coffee break**

Afternoon Session chaired by **Andon Rangelov**

15:20-16:00 **Germano Montemezzani**, *Generation of radially and azimuthally structured vectorial beams by polarization-scrambled cascaded conical diffraction*

16:00-16:40 **Haim Suchowski**, *Broadband and ultrafast near-field spectroscopy and imaging*

16:40-17:10 **Coffee break**

Evening Session chaired by **Stephane Guerin**

17:10-17:50 **Nati Aharon**, *High resolution sensing of high-frequency fields with continuous dynamical decoupling*

17:50-18:20 **Tom Dowdall**, *Trapping and cooling particles using a moving atom diode and an atomic mirror*

18:20-18:40 **Lachezar Simeonov**, *Dynamical invariants for pseudo-Hermitian Hamiltonians*

List of Abstracts

HIGH RESOLUTION SENSING OF HIGH-FREQUENCY FIELDS WITH CONTINUOUS DYNAMICAL DECOUPLING

N. Aharon

Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel

email: nati.aharon@gmail.com

State-of-the-art methods for sensing weak AC fields are only efficient in the low frequency domain (<10 MHz). The inefficiency of sensing high-frequency signals is due to the lack of ability to use dynamical decoupling. In this work we show that dynamical decoupling can be incorporated into high-frequency sensing schemes and by this we demonstrate that the high sensitivity achieved for low frequency can be extended to the whole spectrum. While our scheme is general and suitable to a variety of atomic and solid-state systems, we experimentally demonstrate it with the nitrogen-vacancy center in diamond. We achieve coherence times up to 1.43 ms resulting in a smallest detectable magnetic field strength of 4 nT at 1.6 GHz. Attributed to the inherent nature of our scheme, we observe an additional increase in coherence time due to the signal itself. In this talk I will also present a few other dynamical decoupling schemes, that could be utilized to further improve the resolution of sensing oscillating signals, and in particular, high frequency fields.

QUANTUM TECHNOLOGIES: CLOSING THE CONTROL LOOP

T. Calarco

University of Ulm, Institute of Complex Quantum Systems, Albert-Einstein-Allee, 11, 89069 Ulm, Germany

email: tommaso.calarco@uni-ulm.de

Fully autonomous precise control of qubits is crucial for quantum information processing, quantum communication, and quantum sensing applications. It requires minimal human intervention on the ability to model, to predict and to anticipate the quantum dynamics, as well as to precisely control and calibrate single qubit operations. Based on our improved quantum optimal control DCRAB algorithm including optimization landscape engineering [1], we demonstrate single qubit autonomous calibrations via closed-loop optimisations of electron spin quantum operations in diamond. The operations are examined by quantum state and process tomographic measurements at room temperature, and their performances against systematic errors are iteratively rectified by an optimal pulse engineering algorithm. We achieve [2] an autonomous calibrated fidelity up to 1.00 on a time scale of minutes for a spin population inversion and up to 0.98 on a time scale of hours for a Hadamard gate within the experimental error of 2%. These results manifest a full potential for versatile quantum technologies.

TRAPPING AND COOLING PARTICLES USING A MOVING ATOM DIODE AND AN ATOMIC MIRROR

T. Dowdall

University College Cork (UCC), College Road, Cork City

email: t.dowdall@umail.ucc.ie

We propose a theoretical scheme for atomic cooling, i.e., the compression of both velocity and position distribution of particles in motion. This is achieved by collisions of the particles with a combination of a moving atomic mirror and a moving atom diode. An atom diode is a unidirectional barrier, i.e., an optical device through which an atom can pass in one direction only. We show that the efficiency of the scheme depends on the trajectory of the diode and the mirror. We examine both the classical and quantum mechanical descriptions of the scheme, along with the numerical simulations to show the efficiency in each case.

COHERENT INTERNAL STATE MANIPULATION OF SINGLE ATOMIC AND MOLECULAR IONS BY OPTICAL FREQUENCY COMBS

M. Drewsen

Department of Physics and Astronomy, Aarhus University, Denmark

email: drewsen@phys.au.dk

Coherent manipulation of state-prepared molecular ions are of interest for a wide range of research fields, including ultra-cold chemistry, ultra-high resolution spectroscopy for test of fundamental physics, and quantum information science. Recently, there has been significant advances with respect to both preparing trapped molecular ions in their quantized motional ground state [1-3], and controlling their rovibrational degrees of freedom through a series

of different techniques [4-11]. This talk will focus on coherent manipulation of the internal states of single atomic and molecular ions through the exposure of such ions to optical frequency comb (OFC) [12, 13]. Based on recent coherent manipulations of the population between the metastable 3d $^2D_{3/2}$ and 3d $^2D_{5/2}$ levels in the Ca^+ ion separated by 1.8 THz, we will discuss next experiments on coherent rotational state manipulation of the MgH^+ ion, as well as comment on the perspective of using this manipulation technique in connection coherently controlled reaction experiments.

[1] G. Poulsen, PhD thesis, Aarhus University, 2011.
[2] Y. Wan et al., Phys. Rev. A 043425, 91 (2015).
[3] R. Rugango et al., New J. Phys. 03009, 17 (2015).
[4] P. F. Staanum et al., Nat. Phys. 271, 6 (2010).
[5] T. Schneider et al., Nat. Phys. 275, 6 (2010).
[6] X. Tong et al., Phys. Rev. Lett. 143001, 105 (2010).
[7] W. G.Rellergert et al., Nature 490, 495 (2013).
[8] A. K. Hansen et al., Nature 76, 508 (2014).
[9] C.-Y. Lien et al., Nat. Comm. 4783, 5 (2014).
[10] F. Wolf et al., Nature 457, 530 (2016).
[11] C.-W. Chou et al., Nature 203, 545 (2017).
[12] D. Hayes et al., Phys. Rev. Lett. 140501, 104 (2010).
[13] S. Ding and D. N. Matsukevich, New J. Phys. 023028, 12 (2012); D. Leibfried, ibid., 023029, 12 (2012).

DECAY OF QUANTUM SYSTEMS ANALYSED WITH PSEUDOMODES OF RESERVOIR STRUCTURES

B. Garraway
Department of Physics and Astronomy, University of Sussex, UK
email: b.m.garraway@sussex.ac.uk

Reservoir structures result from certain types of non-uniform bath spectral density with canonical examples such as that of an atom in a cavity. When these structures are coupled to simple quantum systems the resulting decay can be analysed by the method of "pseudomodes", where the reservoir structure is replaced by an effective mode [1]. The approach is useful for strongly coupled, i.e. non-Markovian problems, since exact master equations can be derived. In this talk, an introduction to the basics of pseudomode theory will be given, together with developments on reservoir memory [2, 3] and entanglement in such reservoir structures [4]. Our latest results involving an analysis of multiple observers will be presented [5].

[1] B.M. Garraway, Phys. Rev. A **55**, 4636 (1997).

[2] L. Mazzola, S. Maniscalco, J. Piilo, K.-A. Suominen, and B.M. Garraway, Phys. Rev. A. **80**, 012104 (2009).

[3] G. Pleasance and B.M. Garraway, in preparation (2017).

[4] B.M. Garraway, J. Piilo, and S. Maniscalco, J. Phys. B **44**, 065505 (2011).

[5] G. Pleasance and B.M. Garraway, Phys Rev A **96**, 062105 (2017).

COHERENCE AND NONLINEAR SPECTROSCOPY IN NV DIAMOND

W. Gawlik

Instytut Fizyki Uniwersytet Jagiellonski, Profesora Lojasiewicza 11, 30-348 Krakow, Poland

email: gawlik@uj.edu.pl

Nitrogen-Vacancy (NV-) color centers in diamond are characterized by a nonzero electron spin (S=1) which allows them to be optically pumped and probed via microwave (MW) spectroscopy. In our study we focus on the case of two MW fields tuned to the transitions between the m=0 $\leftrightarrow$ $m = \pm$ 1 spin sublevels of the NV-ensemble in the 3A ground state. One field saturates the transition (burns a hole) while the second is acting as the probe field. The fluorescence intensity reflects the spin state populations and enables monitoring of the optically detected magnetic resonance (ODMR). The recorded spectra are more complex spectra than the standard ODMR ones and exhibit hole burning effect positioned at the pump-field frequency. We found different behavior of the spectra when the pump and probe microwave fields are tuned to either the same or distinct transitions and interpret the difference as a result of coherent population oscillations (CPO). The hole-burning method enables isolation of the homogeneous contribution to the magnetic-resonance width on the background of inhomogeneous broadening and may become a powerful toll for studies of the line broadening issues in NV- diamonds. In particular, I will demonstrate its possible applications to study powders and suspensions of nanodiamonds.

EXPERIMENTAL DEMONSTRATION OF COMPOSITE STIMULATED RAMAN ADIABATIC PASSAGE

G. Genov

Institut für Angewandte Physik, Technische Universitt Darmstadt, Hochschulstrasse 6, 64289 Darmstadt, Germany

email: genko.genov@physik.tu-darmstadt.de

Efficient and robust population transfer by external fields remains an important challenge in many areas of physics. Resonant pulses can deliver high efficiency but are not robust to even the slightest experimental imperfections. Composite pulses are sequences of pulses with suitable relative phases and improved performance with applications in nuclear magnetic resonance and quantum optics. Adiabatic techniques are another useful alternative, e.g., stimulated Raman adiabatic passage (STIRAP) is widely used in physics and chemistry, but its fidelity is limited by imperfect adiabaticity. A combination of STIRAP with composite pulses, composite STIRAP (CSTIRAP), has been proposed recently to address these limitations [1].

We present here the first proof-of-principle experimental implementation of CSTIRAP by applying it for population transfer between the hyperfine ground states of Pr atoms in a rare-earth doped solid. We compare the performance with traditional STIRAP and show that CSTIRAP improves both the robustness and peak transfer efficiency substantially in comparison to repeated STIRAP in the regime of large single photon detuning. In the latter, STIRAP is insensitive to the initial state of the system, which makes it suitable for repeated inversion processes, e.g. for rephasing of atomic coherences for quantum memories. Our experimental findings match very well the corresponding numerical simulations.

[1] B. T. Torosov and N. V. Vitanov, Phys. Rev. A **87**, 043418 (2013).

EXACTLY SOLVABLE GENERALIZED RABI SYSTEMS

R. Grimaudo

Dipartimento di Fisica e Chimica dell'Universita di Palermo, Via Archirafi, 36, I-90123 Palermo, Italy

email: roberto.grimaudo01@unipa.it

The exact quantum dynamics of a single spin-1/2 in a generic time-dependent classical magnetic field is investigated and compared with the quantum motion of a spin-1/2 studied by Rabi and Schwinger. The possibility of regarding the scenario studied in this paper as a generalization of that considered by Rabi and Schwinger is discussed and time-dependent resonance and out of resonance conditions are introduced and carefully legitimated and analysed. Several examples help to disclose analogies and departures of the quantum motion induced in a generalized Rabi system with respect to that exhibited by the spin-1/2 in a magnetic field precessing around the z-axis. We find that, under generalized resonance condition, the time evolution of the transition probability $P_+^-(t)$ between the two eigenstates of $\hat{S}^z$ may be dominated by a regime of distorted oscillations, or may even exhibit a monotonic behaviour. At the same time we succeed in predicting no oscillations or even oscillations of maximum amplitude in the behaviour of $P_+^-(t)$ under generalized out of resonance condition. New scenarios of experimental interest originating a Landau-Zener transition is brought to light.

ROBUST CONTROL OF LINEAR AND NON-LINEAR QUANTUM SYSTEMS BY SHAPED PULSES

S. Guerin

Laboratory ICB - University Bourgogne - France

email: sguerin@u-bourgogne.fr

The control of quantum systems by external fields (laser) possibly combined with cavity QED or plasmonic field is at the heart of modern applications ranging from quantum information processing to the control of chemical reactions. It can be in general formulated as the transfer from an initial to a target state for photonic [1], atomic [2], molecular [3], and quantum dot states [4].

One challenging issue is the ability to achieve a high-fidelity transfer to a given target state in a robust way with respect to fluctuations, the partial knowledge of the system, and decoherence. This can be achieved by the single-shot shaped pulse technique [5-7], which extends the composite pulse method [8]. Its extension to non-linear quantum systems, such as the one featuring the production of molecular Bose-Einstein condensates from atomic ones, is presented [9].

[1] A. Gogyan, S. Guerin, C. Leroy, and Yu. Malakyan, Phys. Rev. A **86**, 063801 (2012).

[2] B. Rousseaux, S. Guerin, and N.V. Vitanov, Phys. Rev. A **87**, 032328 (2013).

[3] M. Sala, M. Saab, B. Lasorne, F. Gatti, and S. Guerin, J. Chem. Phys. **140**, 194309 (2014).

[4] B. Rousseaux, D. Dzsotjan, G. Colas des Francs, H.R. Jauslin, C. Couteau, and S. Guerin, Physical Review B **93**, 045422 (2016); Erratum, Phys. Rev. B **94**, 199902 (2016).

[5] D. Daems, A. Ruschhaupt, D. Sugny, and S. Guerin, Phys. Rev. Lett. **111**, 050404 (2013).

[6] L. Van-Damme, D. Schraft, G.T. Genov, D. Sugny, T. Halfmann, and S. Guerin, Phys. Rev. A **96**, 022309 (2017).

[7] H. Jo, H. Lee, S. Guerin, and J. Ahn, Phys. Rev. A **96**, 033403 (2017).

[8] B.T. Torosov, S. Guerin, N.V. Vitanov, Phys. Rev. Lett. **106**, 233001 (2011).

[9] V. Dorier, M. Gevorgyan, A. Ishkhanyan, C. Leroy, H.R. Jauslin, and S. Guerin, Phys. Rev. Lett. **119**, 243902 (2017).

TOWARDS ENTANGLEMENT BETWEEN DISPARATE MATTER QUANTUM NODES

G. Heinze

ICFO – The Institute of Photonic Sciences, Av. Carl Friedrich Gauss 3, 08860 Castelldefels (Barcelona), Spain

email: georg.heinze@icfo.eu

Building quantum networks - consisting of matter quantum nodes and photonic communication channels - is a key to enable future distributed quantum information applications. In this talk, we first briefly report on our recent efforts to build the first hybrid quantum interface connecting a cold ensemble of Rubidium atoms and a Praseodymium-ion doped crystal [1]. We show that a paired single photon from the cold atomic ensemble can be frequency converted to the telecom C-band and back to the visible range to be stored and retrieved in the solid-state memory. Using time-bin encoding, we afterwards demonstrate that a qubit can be faithfully transferred between the disparate quantum systems. To further expand the capabilities of that approach, one would like to achieve entanglement between both matter systems. In the second part of the talk, we discuss how this goal can be reached. To that end, we demonstrate the first direct generation of entanglement between a photonic time-bin qubit and a single collective atomic spin excitation (spin wave) in the cold atomic ensemble [2]. A magnetic field that induces a periodic dephasing and rephasing of the atomic excitation ensures the temporal distinguishability of the two time bins and plays a central role in the entanglement generation. We analyze the generated quantum state by performing projective measurements in different qubit bases and verify the entanglement by violating a CHSH Bell inequality.

[1] N. Maring, P. Farrera, K. Kutluer, M. Mazzera, G. Heinze, H. de Riedmatten, Nature 551, 485 (2017).

[2] P. Farrera, G. Heinze, H. de Riedmatten, arXiv:1801.05723 (2018).

INTERACTING RYDBERG IONS

M. Hennrich

AlbaNova University Center, Stockholm University, Department of Physics, SE 106 91 Stockholm, Sweden

email: markus.hennrich@fysik.su.se

Trapped Rydberg ions are a novel quantum system [1,2], just recently observed for the first time [3,4]. They bring together two leading quantum technologies: trapped ions and Rydberg atoms. For trapped ions, this technology promises to speed up entanglement operations and make them available in larger ion crystals. I will present our recent experimental results using trapped $^{88}\mathrm{Sr}_6^+$ Rydberg ions. In particular, this includes the first coherent excitation of an ion to the Rydberg state, the realization of a single-qubit Rydberg phase gate [5], and the observation of Rydberg blockade between two microwave-dressed Rydberg ions. These are important steps towards realizing a quantum simulator with trapped Rydberg ions.

[1] M. Mller, et al., New J. Phys. **10**, 093009 (2008).

[2] F. Schmidt-Kaler, et al., New J. Phys. **13**, 075014 (2011).

[3] T. Feldker, et al., Phys. Rev. Lett. **115**, 173001 (2015).

[4] G. Higgins, et al., Phys. Rev. X **7**, 021038 (2017).

[5] G. Higgins, et al., Phys. Rev. Lett. **119**, 220501 (2017).

CONSTRUCTING A MULTI-MODULE TRAPPED-ION QUANTUM COMPUTER PROTOTYPE

W. Hensinger

Sussex Centre for Quantum Technologies, Department of Physics and Astronomy, University of Sussex, Falmer, Brighton, East Sussex, BN1 9QH, United Kingdom

email: w.k.hensinger@sussex.ac.uk

I will discuss progress in constructing a multi-module trapped-ion quantum computer prototype at the University of Sussex. I will provide a short overview of the overall architecture. Previously, it had been proposed to use photonic interconnects to connect individual computer modules. Our new invention introduces connections created by electric fields that allow ions to be transported from one module to another. This architecture also features a method where quantum gates with trapped ions are executed by applying voltages in the presence of a few global rf radiation fields similar in nature to the operation of transistors in a classical computer. I will also describe a coherent control method to make quantum gates more resilient to parameter fluctuations and show experimental results. Finally I will discuss a technique to transform existing two-level quantum control methods to new multi-level control methods and provide an application of this method where we map two different qubit types coherently with a fidelity well above the relevant fault-tolerant threshold.

ADIABATIC THREE-WAVEGUIDE COUPLER

H. Hristova

Institute of Solid State Physics, Bulgarian Academy of Sciences, 72 Tsarigradsko Chaussee, 1784 Sofia, Bulgaria

email: hhristova@issp.bas.bg

We propose an adiabatic method for transfer of light in a three-waveguide directional coupler in a single mode[1]. In our scheme the propagation coefficients of the two outer waveguides are identical, but may vary simultaneously along the propagation direction. Here we may have initially any light input in each of the waveguides and any order of coupling coefficients. Consequently, all three adiabatic eigenstates of the system are used in the dynamics. These solutions allow us to design some interesting waveguide devices.

Acknowledgement: Further investigations are supported by the Bulgarian Academy of Science Programme for young scientists and PhD students 2017.

[1] H. S. Hristova, A. A. Rangelov, G. Montemezzani and N. V. Vitanov, Phys. Rev A. **93**, 033802 (2016).

ION-PHOTON INTERFACES FOR QUANTUM NETWORKS

M. Keller

University of Sussex, Pevensey 2, Brighton BN1 9QH, UK

email: m.k.keller@sussex.ac.uk

The complementary benefits of trapped ions and photons as carriers of quantum information make it appealing to combine them in a joint system. Ions provide low decoherence rates, long storage times and high readout efficiency, while photons are ideal candidates for the transmission of quantum states over long distances. To interface the quantum states of ions and photons efficiently, we use calcium ions coupled to an optical high-finesse cavity via a Raman transition. To achieve strong ion-cavity coupling we employ fibre tip cavities integrated into the electrodes of an endcap style ion trap. With a cavity length of 380 mm the resulting ion-cavity coupling strength is 17 MHz with a cavity line width of 8 MHz. We trap single calcium ions with a life time of several hours and have optimised the ion-cavity overlap to observe the interaction of the cavity with the ion. While fibre cavities are ideal tools for ion-photon interfaces the limited coupling between the cavity mode and the fibre mode poses severe limitations on their usability in efficient quantum interfaces. We have developed a system to integrate mode matching optics into a fibre system and have demonstrated a mode matching between cavity and fibre on the order of 90%. In another experiment we have demonstrated the quantum frequency conversion of single photons from an ion-cavity system from a wavelength of 866 nm to the telecom wavelength of 1550 nm. The quantum nature of the single photon emission is well preserved and we have demonstrated the transmission of frequency converted single photons over a 10 km long optical fibre.

THREE-PHOTON PRECISION SPECTROSCOPY OF A LARGE ION CLOUD

M. Knoop

Aix-Marseille Universite, CNRS, PIIM, UMR 7345, 13397 Marseille, France

email: martina.knoop@univ-amu.fr

Coherent population trapping allows to exploit multi-photon spectroscopy with a very high precision [1]. The right combination of three wavevectors gives rise to a scheme which is inherently Doppler-free. A cloud of trapped ions is then an excellent sample to measure, for example, transition dipoles with an uncertainty inferior to 10^{-3}, necessary to push forward todays best calculations [2]. The experimental observation of a three-photon dark line in an ion cloud is explored and its building blocks will be presented. The set-up relies on a linear radio-frequency trap where up to 10^6 laser-cooled Ca^+ ions can be trapped. We have developed and realized a narrow linewidth laser at 729 nm that reaches a relative frequency stability below 10^{-14} per second for periods inferior to 10 seconds to probe the electric quadrupole transition. The required fixed phase-relation of this source and the two cooling lasers is reached by simultaneous lock on a frequency comb. Measurements are ongoing and results will be reported at the conference [3].

[1] C. Champenois, et al., Phys. Rev. Lett. **99**, 013001 (2007).

[2] M. S. Safronova et al., Phys. Rev. A **83**, 012503 (2011).

[3] R. Khayatzadeh, et al., IEEE Photonics Technology Letters **29**, 322-325 (2017).

ELEMENTS OF A CAVITY-BASED ATOM-ATOM ENTANGLER

A. Kuhn

University of Oxford, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, United Kingdom

email: axel.kuhn@physics.ox.ac.uk

Probabilistic entanglement of distant atoms can be achieved by entanglement swapping acting on photons emitted from both atoms. Here we discuss the essential first step, namely the photon generation in a cavity, in a real-world scenario [1]. In particular we focus on polarisation control and spin-polarisation coupling in a birefringent optical cavity, and we do also take non-linear Zeeman shifts into account. Furthermore we demonstrate quantum logic [2], feedback [3] and supremacy when operating integrated photonic chips with cavity photons.

[1] T. Barrett et al., in preparation.

[2] A. Holleczek et al., Phys. Rev. Lett. **117**, 023602 (2016).

[3] O. Barter et al., in preparation.

BOSONIC COMPLEX QUANTUM NETWORKS: WHAT, WHEN AND WHY

S. Maniscalco

Department of Physics and Astronomy, University of Turku, 20014 Turun yliopisto, Finland

email: smanis@utu.fi

What are bosonic complex quantum networks? Do they exist in Nature? Can they be implemented experimentally? In this talk I will present some perspectives on these questions by looking at Hamiltonian models describing complex networks of quantum harmonic oscillators.

I will first show that such systems are very useful for investigating the properties of open quantum systems, namely quantum systems interacting with an environment. This framework considers one of the nodes as the open system and the other nodes of the network as part of the environment. I will show that, changing the properties of the network, it is possible to engineer ad hoc open quantum dynamics by modifying the spectral density of the environment. This is particularly relevant in connection to quantum technologies where understanding and modelling environmental noise is crucial to realise robust and scalable commercial quantum devices.

With a change in perspective to the complementary view point, the node forming the open quantum system can be seen as a local probe from which one can extract certain properties of the network. Remarkably, we show that global properties can be mapped into the time evolution of the probe hence, measuring the latter one, one can extract them. I will focus in particular on the ability to measure the connectivity of the network by local probing.

Finally, I will briefly present the main ingredients of an experimental implementation of bosonic complex quantum networks using an optical set up. I will argue that, independently of whether or not these systems exist in Nature, the ability to engineer them experimentally has great relevance to both fundamentals of quantum mechanics and applications such as quantum technologies.

GENERATION OF RADIALLY AND AZIMUTHALLY STRUCTURED VECTORIAL BEAMS BY POLARIZATION-SCRAMBLED CASCADED CONICAL DIFFRACTION

G. Montemezzani

Laboratory LMOPS, University of Lorraine and CentraleSupelec, 2 rue E. Belin, F - 57070 Metz

email: germano.montemezzani@univ-lorraine.fr

When a light beam travels along one of the two optical axes of an anisotropic biaxial crystal it experiences conical diffraction (or conical refraction), a phenomenon known since nearly two centuries. The unique propagation vector is then associated to a multitude of different directions for the Poynting vector, all propagating on the surface of a cone and each one associated to a different linear polarization. The last 15 years or so have witnessed a strong renewed interest in this peculiar and fascinating effect, principally due to several promising applications in modern photonics. One of the major recent advances consists in the development of cascaded configurations, where two or more biaxial crystals with their optical axes aligned are put in series. It was shown that a cascade of N crystals leads to the formation of 2 to the power N-1 concentric cones. In this case the intensity distribution is modulated radially but remains homogeneous in the azimuthal direction, at least in the case of an input light being unpolarized or circularly polarized. Here it will be shown theoretically and experimentally that by introducing some polarization transforming elements (waveplates, polarizers) in between the cascaded crystals the azimuthal light distribution becomes highly structured. Potentially the involved elements can be activated extremely fast by using electro-optical devices, leading to the possibility of a fast reshaping of the complex structure of the vectorial beam.

SUPERADIABATIC POPULATION TRANSFER BY LOOP DRIVING AND SYNTHETIC GAUGES IN A SUPERCONDUCTING CIRCUIT

S. Paraoanu

Low Temperature Laboratory, Department of Applied Physics, Aalto University School of Science, P.O. Box 15100, FI-00076 AALTO, Finland

email: sorin.paraoanu@aalto.fi

The achievement of fast and error-insensitive control of quantum systems is a primary goal in quantum information science. Here we use the first three levels of a transmon superconducting circuit to realize a loop driving scheme, with all three possible pairs of states coupled by pulsed microwave tones. In this configuration, we implement a superadiabatic protocol for population transfer, where two couplings produce the standard stimulated Raman adiabatic passage, while the third is a counterdiabatic field which suppresses the nonadiabatic excitations. We demonstrate that the population can be controlled by the synthetic gauge-invariant phase around the loop as well as by the amplitudes of the three pulses. The technique enables fast operation, with transfer times approaching the quantum speed limit, and it is remarkably robust against errors in the shape of the pulses.

[1] arXiv:1709.03731v1

RECENT PROGRESS TOWARDS QUANTUM LOGIC INSPIRED COOLING AND READOUT TECHNIQUES FOR SINGLE (ANTI-)PROTONS

A. Paschke

Institut fuer Quantenoptik, Leibniz Universitaet Hannover, Welfengarten 1, 30167 Hannover, Germany

email: paschke@iqo.uni-hannover.de

Our research group aims to develop and apply novel laser-based, quantum logic inspired cooling and manipulation techniques to single (anti-)protons in a cryogenic Penning trap system. Within the BASE collaboration [1] this will support ongoing tests of CPT symmetry based on a g-factor comparison between the proton and antiproton by significantly improving the particle localization and detection times. For implementation we have designed a multi-zone Penning trap apparatus, in which a single (anti-)proton will be coupled to a co-trapped “logic” $9Be^+$ ion and be sympathetically cooled, controlled and read out indirectly using quantum logic operations [2,3]. In this contribution we report on the status of the project and present recent experimental results on quantum control of $9Be^+$ ions based on direct frequency comb control [4] using a spectrally tailored UV frequency comb.

[1] Smorra et al., Eur. Phys. J. Special Topics **224**, 3055-3108 (2015).
[2] Heinzen and Wineland, PRA **42**, 2977 (1990).
[3] Wineland et al., J. Res. NIST **103**, 259 (1998).
[4] Hayes et al., PRL **104**, 140501 (2010).

FULLY CONTROLLED DEPHASING DYNAMICS AND SYNTHETIC SPECTRAL DENSITIES

J. Piilo
Department of Physics and Astronomy, University of Turku, Fi-20014 Turun yliopisto, Finland
email: jyrki.piilo@utu.fi

Engineering, controlling, and simulating quantum dynamics is a strenuous task. However, these techniques are crucial to develop quantum technologies, preserve quantum properties, and engineer decoherence. Earlier results have demonstrated reservoir engineering, construction of a quantum simulator for Markovian open systems, and controlled transition from Markovian to non-Markovian regime. Dephasing is an ubiquitous mechanism to degrade the performance of quantum computers. However, a fully controllable all-purpose quantum simulator for generic dephasing is still missing. Here we demonstrate full experimental control of dephasing allowing us to implement arbitrary decoherence dynamics of a qubit [1]. As an example, we use a photon to simulate the dynamics of a qubit coupled to an Ising chain in a transverse field and also demonstrate a simulation of non-positive dynamical map. Our platform opens the possibility to simulate dephasing of any physical system and study fundamental questions on open quantum systems.

[1] Z.-D. Liu et al,. arXiv:1712.08071

SOLID STATE SOURCE OF PHOTON TRIPLETS

A. Predojevic

Stockholm University, Department of Physics, Albanova University Center, Roslagstullsbacken 21, SE-106 91 Stockholm, Sweden

email: ana.predojevic@fysik.su.se

While remarkable progress has been made on single photons and photon pairs, multipartite correlated photon states are usually produced in purely optical systems by post-selection or cascading. On the other hand, multipartite states enable improved tests of the foundations of quantum mechanics as well as implementations of complex quantum optical networks and protocols. Therefore, it would be favorable to directly generate these states using solid state systems, for better scaling, simpler handling, and the promise of reversible transfer of quantum information between stationary and flying qubits. Here, we use the ground states of two optically active coupled quantum dots to directly produce photon triplets. The formation of a triexciton leads to a triple cascade recombination and sequential emission of three photons with strong correlations. The quantum dot molecule is embedded in an epitaxially grown nanowire engineered for single-mode wave-guiding and improved extraction efficiency at the emission wavelength. We record 65.62 photon triplets per minute. Our structure and data represent a breakthrough towards implementing multipartite photon entanglement and multi-qubit readout schemes in solid-state devices, suitable for integrated quantum information processing.

DYNAMICAL INVARIANTS FOR PSEUDO-HERMITIAN HAMILTONIANS

L. Simeonov

Department of Physics, Sofia University St. Kliment Ohridski, 5 James Bourchier Blvd, 1164 Sofia, Bulgaria

email: lsimeonov@phys.uni-sofia.bg

We derive the dynamical invariants for a general N-state quantum system described by a pseudo-Hermitian Hamiltonian. Explicit expressions are presented for two- and three-state systems, which are exemplified by explicit analytic solutions for constant couplings. In the two-state case, we derive non-Hermitian analogs of the Bloch vector and the Bloch equation, customary for Hermitian quantum systems. We suggest possible physical implementations

of the dynamical invariants in waveguide optics and frequency conversion.

BROADBAND AND ULTRAFAST NEAR-FIELD SPECTROSCOPY AND IMAGING

H. Suchowski

Condensed matter Physics department, Tel Aviv University, Israel

email: haimsu@post.tau.ac.il

For the past two decades we have witnessed major advances in nano-optics and ultrafast physics, allowing for the exploration of phenomena in higher spatial and temporal resolution than ever before. In my talk I will share with you our efforts and success in merging these extreme resolution capabilities in order to study ultrafast phenomena at nanoscale resolution. Such developments allows us to observe and in the future to control ultrafast phenomena in a spatio-temporal window of 20fs-15nm at various wavelength regimes from the visible to the mid-infrared. The mid-infrared wavelength regime is of particular importance to materials science, chemistry, biology and condensed matter physics, as it covers the fundamental vibrational absorption bands as well as of many molecules and solid state materials.

In particular, I will present our recent achievements in combining ultrabroadband sources with our scattering near field microscope allowing observation of the broad frequency response as well as the ultrafast transient dynamics of plasmonic systems and in single-layer and multilayer WSe2.

ARBITRARILY ACCURATE TWIN COMPOSITE PULSE SEQUENCES

B. Torosov

Institute of Solid State Physics, Bulgarian Academy of Sciences, 72 Tsarigradsko chaussee, 1784 Sofia, Bulgaria

email: torosov@issp.bas.bg

We present three classes of symmetric broadband composite pulse sequences. The composite phases are given by analytic formulas valid for any number of constituent pulses. The transition probability is expressed by simple analytic formulas and the order of pulse area error compensation grows linearly with the number of pulses. Therefore, any desired compensation order can be produced by an appropriate composite sequence; in this sense, they are arbitrarily accurate. These composite pulses perform equally well or better than previously published ones. Moreover, the current sequences are more flexible as they allow total pulse areas of arbitrary integer multiples of π. The work is supported by the Bulgarian Science Fund Grant DN18/14.

FIBER AMPLIFIERS AND THEIR APPLICATIONS IN DOPPLER COOLING AND QUANTUM KEY DISTRIBUTION

T. Walther

Institute for Applied Physics, TU Darmstadt, Schlossgartenstr. 7, D-64289 Darmstadt, Germany

email: thomas.walther@physik.tu-darmstadt.de

In recent years, we have pursued experiments where narrowband cw radiation or Fourier-transform (FT) limited pulses are a requirement. We therefore ventured into exploring the possibilities of fiber amplifiers as they enable fulfilling these specifications in a relatively straight forward manner. In some cases this was combined with the need of non-linear frequency conversion into the UV spectral range.

During the first part of the talk, we will detail some of the physics and experimental features of our cw and pulsed fiber amplifiers. In particular, we describe a cw system frequency quadrupled into the UV [1], a fiber amplifier with FT-limited ns-pulses [2] as well as an advanced version producing ps-pulses with flexible pulse duration at high repetition rates [3].

The second part is dedicated to the discussion of two applications of these fiber amplifiers in our laboratory. The first is the transfer of the ideas of Doppler cooling to cooling highly relativistic ion beams in accelerators. Instead of stopping the ion beam, the goal of this experiment is to considerably narrow the momentum distribution. We will introduce the motivation for such experiments and the basic steps in order to achieve such cooling as well as first results. Lastly, we present an experiment in quantum key distribution (QKD) geared towards the setup of a quantum hub intended as a basic building block of a small QKD network.

[1] T. Beck, B. Rein, F. Sörensen, and T. Walther, Opt. Lett. **41**, 4186–4189 (2016).
[2] Kai Schorstein and Thomas Walther, Appl. Phys. B **97**, 591–597 (2009).
[3] Daniel Kiefer and Thomas Walther, submitted to CLEO (2018).

SPEEDING-UP THE DECISION MAKING OF A LEARNING AGENT USING AN ION TRAP QUANTUM PROCESSOR

C. Wunderlich
Department of Physics, Universität Siegen, 57068 Siegen, Germany
email: christof.wunderlich@uni-siegen.de

We report a proof-of-principle experimental demonstration of the quantum speed-up for learning agents utilizing a small-scale quantum information processor based on radiofrequency-driven trapped ions [1]. The decision-making process of a quantum learning agent within the projective simulation paradigm for machine learning is implemented in a system of two qubits. The latter are realized using hyperfine states of two frequency-addressed atomic ions exposed to a static magnetic field gradient. We show that the deliberation time of this quantum learning agent is quadratically improved with respect to comparable classical learning agents. The performance of this quantum-enhanced learning agent highlights the potential of scalable quantum processors taking advantage of machine learning.

[1] Th. Sriarunothai et al., arXiv: 1709.01366 (2017).

OPTICALLY STIMULATED THIRD HARMONIC GENERATION

K. Zlatanov
Hochschulstr. 6D-64289 Darmstadt, Germany
email: k.zlatanoff@gmail.com

Coherent nonlinear microscopy (CNM) is widely used in three-dimensional imaging of transparent samples, particularly for biological tissues [1]. Examples for parametric and label free CNM processes are second harmonic generation (SHG) and third harmonic generation (THG). However, working under far off-resonant excitation conditions usually leads to low optical conversion efficiencies. Hence, the typically low signals may lead to a bad signal-to-noise ratio and low image contrast. There are several approaches to enhance the signal yield in CNM, e.g. using dispersion to optimize the phase-matching integral [2]. One promising concept is the "Enhancement of Second-Order Nonlinear-Optical Signals by Optical Stimulation" [3]. The basic idea is to stimulate a nonlinear signal by already "seeding" with some radiation at the harmonic frequency. The previous and first demonstration of the concept for SHG yielded signal enhancements more than 10 in a biologically relevant medium. We present strong enhancements of third harmonic generation by optical stimulation in a microscopy setup. The effect is most pronounced at low laser intensity and weak nonlinear susceptibilities, making it suitable in harmonic microscopy.

[1] S. Yue, M.N. Slipchenko, J.-X. Cheng, Laser Photon. Rev. **5**, 496512 (2011).

[2] Ch. Stock, K. Zlatanov, and Th. Halfmann, Optics Communications Vol. **393**, 289-293 (2017).

[3] A. J. Goodman and W. A. Tisdale, Phys. Rev. Lett. **114**, 183902 (2015).

Index

CAMEL XIV Programme

Time	Mon, March 12	Tue, March 13	Wed, March 14	Thu, March 15
13:30-14:10	Maniscalco	Calarco	Walther	Guerin
14:10-14:50	Garraway	Piilo	Kuhn	Knoop
14:50-15:20	coffee	coffee	coffee	coffee
15:20-16:00	Hennrich	Wunderlich	Gawlik	Montemezzani
16:00-16:40	Drewsen	Hensinger	Keller	Suchowski
16:40-17:10	coffee	coffee	coffee	coffee
17:10-17:50	Predojevic	Heinze	Paraoanu	Aharon
17:50-18:20	Paschke	Genov	Torosov	Dowdall
18:20-18:40	Grimaudo	Calarco	Zlatanov	Simeonov
18:40-19:00			Hristova	
20:00		**conf. dinner**		

The conference dinner will take place on Tuesday, March 13, starting at 20:00.