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

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BOOK OF ABSTRACTS

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Programme

Monday, June 23

Morning Session chaired by **Thomas Halfmann**

09:00-09:40 **Matthias Wollenhaupt**, *Recent developments in multiphoton photoelectron circular dichroism (PECD)*

09:40-10:20 **Barry Bruner**, *Enhancement of high harmonic generation using two-colour laser fields*

10:20-10:50 **Coffee break**

Noon Session chaired by **Kilian Singer**

10:50-11:30 **Christof Wunderlich**, *Addressing a quantum byte and robust dynamical decoupling for conditional quantum gates*

11:30-12:10 **Winfried Hensinger**, *Microwave quantum logic and architectures for quantum technology with ions*

12:10-12:40 **Hiroki Takahashi**, *Interfacing single ions and photons via cavity QED*

Lunch

16:30-17:00 **Coffee break**

Evening Session chaired by **Matthias Wollenhaupt**

17:00-17:40 **Thorsten Peters**, *Preparation of an ultracold medium at extreme optical depth*

17:40-18:00 **Tim Bayer**, *Resonant strong-field control of coherent electron dynamics*

18:00-18:20 **Hendrike Braun**, *Selective excitation of electronic states in* K_2

18:20-18:40 **Boyan Torosov**, *Improvement of adiabaticity: composite pulses and non-Hermitian shortcuts*

18:40-19:00 **Andon Rangelov**, *Robust and broadband frequency conversion in nonlinear composite crystals*

19:00-19:20 **Genko Genov**, *Efficient and broadband frequency generation by composite crystals*

Tuesday, June 24

Morning Session chaired by **Thomas Walther**

09:00-09:40 **Thomas Halfmann**, *Storing images up to one minute by EIT in a doped solid*

09:40-10:20 **Axel Kuhn**, *Coding of qubits, qutrits and ququads in cavity-QED photons*

10:20-10:50 **Coffee break**

Noon Session chaired by **Winfried Hensinger**

10:50-11:30 **Michael Drewsen**, *Rotational cooling of Coulomb-crystallized molecular ions by a helium buffer gas*

11:30-12:10 **Markus Hennrich**, *Experimental quantum computations on a topologically encoded qubit*

12:10-12:40 **Hsiang-Yu Lo**, *Nonclassical state preparations by reservoir engineering in an ion trap*

Lunch

16:30-17:00 **Coffee break**

Evening Session chaired by **Thorsten Peters**

17:00-17:40 **Barry Garraway**, *Dressed-up for quantum technology*

17:40-18:00 **Georg Heinze**, *Rephasing of single spin excitations for temporally multiplexed quantum memories*

18:00-18:20 **Margherita Mazzera**, *Quantum storage of heralded single photons in a Pr-based solid-state memory*

18:20-18:40 **Daniel Schraft**, *Universal composite pulses for rephasing of atomic coherences in a doped solid*

18:40-19:00 **Simon Mieth**, *Solid-state, high power, tunable cw laser system for quantum optics applications*

Wednesday, June 25

Morning Session chaired by **Barry Bruner**

09:00-09:40 **Germano Montemezzani**, *Quantum-like phenomena and nonlinear optical frequency conversion in coupled waveguides*

09:40-10:20 **Dragomir Neshev**, *Generation of entangled photons in nonlinear adiabatic waveguiding structures*

10:20-10:50 **Coffee break**

Noon Session chaired by **Christof Wunderlich**

10:50-11:30 **Kilian Singer**, *Deterministic ion source realizing nanometer resolution and thermodynamics with trapped ions*

11:30-12:10 **Alex Retzker**, *Increasing sensing resolution with error correction*

12:10-12:40 **Max Tillmann**, *BosonSampling with controllable distinguishability*

Lunch

13:30-18:30 **Social event**

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Morning Session chaired by **Wojciech Gawlik**

09:00-09:40 **Pierre Pillet**, *Three-body Forster resonances in frozen Rydberg gases*

09:40-10:20 **Thomas Walther**, *Towards lasing without inversion in neutral mercury*

10:20-10:50 **Coffee break**

Noon Session chaired by **Barry Garraway**

10:50-11:30 **Hans-Rudolf Jauslin**, *Adiabatic control of nonlinear quantum systems; applications to molecular Bose-Einstein condensates*

11:30-12:10 **Stéphane Guérin**, *Robust control of linear and non-linear quantum systems by shaped pulses*

12:10-12:40 **Etienne Brion**, *Quantum information with Rydberg blocked atomic ensembles*

Lunch

16:30-17:00 **Coffee break**

Evening Session chaired by **Stéphane Guérin**

17:00-17:40 **Ignacio Sola**, *Coherent electronic motion in femtoscale: generating giant molecular antennas*

17:40-18:00 **Bo Young Chang**, *Creating and controlling oscillating molecular dipoles under strong fields*

18:00-18:20 **Andrey Grankin**, *Quantum statistics of light transmitted through an intracavity Rydberg medium*

18:20-19:00 **Janne Salo**, *European Research Council funding opportunities under Horizon2020*

20:30 **Conference dinner**

Friday, June 27

Morning Session chaired by **Filippo Caruso**

09:00-09:40 **Sabrina Maniscalco**, *Witnessing entanglement in hybrid systems*

09:40-10:20 **Jyrki Piilo**, *Some fundamental aspects and applications of non-Markovian quantum dynamics*

10:20-10:50 **Coffee break**

Noon Session chaired by **Sabrina Maniscalco**

10:50-11:30 **Wojciech Gawlik**, *Coherence effects in cold rubidium atoms*

11:30-11:50 **Svetoslav Ivanov**, *Quantum Fourier transform with trapped ions*

11:50-12:10 **Peter Ivanov**, *Quantum simulation of superexchange magnetism in linear ion crystal*

12:10-12:40 **Filippo Caruso**, *How to control atom-chip coherent dynamics*

Lunch

16:30-17:00 **Coffee break**

Evening Session chaired by **Svetoslav Ivanov**

17:00-17:20 **Teodora Kirova**, *Peculiarities of bright and dark states formation in 3D3/2 and 5D5/2 Na states*

17:20-17:40 **Benjamin Rousseaux**, *Production of photon states using* Λ*-atoms in a cavity*

17:40-18:00 **Tatiana Ivanova**, *Feedback cooling of thermal atoms using Bragg scattering*

18:00-18:20 **Denis Ivanov**, *Feedback-enhanced spatial organization of Bose-Einstein condensate in an optical lattice*

18:20-18:40 **Lachezar Simeonov**, *Exactly solvable two-state quantum model for a pulse of hyperbolic-tangent shape*

List of Abstracts

RESONANT STRONG-FIELD CONTROL OF COHERENT ELECTRON DYNAMICS

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Direct ultrafast manipulation of electron motion has emerged as a new perspective in chemical reaction control. Efficient steering of photochemical events is achieved by intense femtosecond laser pulses, precisely tailored to the laser-induced charge dynamics. Recently we reported on a fundamental mechanism of resonant strong-field control based on the Selective Population of Dressed States (SPODS) [Wollenhaupt et al.: CPL 419, 184-190 (2006)]. The scenario allows ultrafast switching of electronic excitation between different target channels with high efficiency and selectively. The potential of SPODS for efficient ultrafast switching is discussed on a generic multi-level system and demonstrated experimentally on the strong-field control of concerted electron-nuclear dynamics in potassium molecules.

SELECTIVE EXCITATION OF ELECTRONIC STATES IN K_2

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Recently we reported on the selective excitation of K_2 using spectrally phase-shaped femtosecond laser pulses [1]. A detailed analysis of quantum dynamic simulations reveals the mechanism at play [2]. By bespoke tailoring of the electric field the coupled electron-nuclear dynamics in molecules are steered. In this way we can manipulate the delicate interplay between the driving laser field and the light induced dynamics in the molecule and efficiently populate different target channels not accessible in the perturbative excitation regime. In addition first experimental evidence shows that femtosecond laser pulses, that are shaped with spectral phases consisting of second and third order polynomial modulation [3], offer a high degree of control over the populations in selected electronic states of the potassium dimer.

[1] T. Bayer et al., Phys. Rev. Lett. **110**, 123003 (2013).

[2] H. Braun et al., J. Phys. B., in print (2014).

[3] J. Schneider et al., Phys. Chem. Chem. Phys. **13**, 8733 (2011).

QUANTUM INFORMATION WITH RYDBERG BLOCKED ATOMIC ENSEMBLES

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Neutral atoms are one of the candidates for the physical implementation of a quantum processor. Most of the proposals in atomic quantum information are based on the very strong dipole-dipole interaction which exists between highly excited atoms (Rydberg atoms) [1]. In an atomic ensemble, this interaction – and the energy shifts it results in, may be strong enough to forbid the resonant excitation of the sample into multiply Rydberg excited states, leading to the so-called Rydberg blockade [2]. We proposed to use this phenomenon to encode quantum information in the highly entangled collective symmetric states of an atomic ensemble [3,4]. This storage procedure is robust [5] and the information thus encoded can be processed in a very practical way, only through collective manipulations of the ensembles [4]. In this talk, I shall briefly summarize the basic features of our collective encoding scheme and I will evoke some of its possible uses in quantum computation [6], quantum simulation [7] and quantum communication [8].

[1] M. Saffman, T. G. Walker, and K. Molmer, Rev. Mod. Phys. **82**, 2313 (2010).

[2] M. D. Lukin et al., Phys. Rev. Lett. **87**, 037901 (2001).

[3] E. Brion, A. S. Mouritzen, and K. Molmer, Phys. Rev. A **76**, 022334 (2007).

[4] E. Brion, K. Molmer, and M. Saffman, Phys. Rev. Lett. **99**, 260501 (2007).

[5] E. Brion et al., Phys. Rev. Lett. **100**, 110506 (2008).

[6] E. Brion et al., Quantum Computers and Computing **10**, 26 (2010).

[7] C. Guerlin, E. Brion, T. Esslinger, and K. Molmer, Phys. Rev. A **82**, 053832 (2010).

[8] E. Brion, F. Carlier, V. M. Akulin, and K. Molmer, Phys. Rev. A **85**, 042324 (2012).

ENHANCEMENT OF HIGH HARMONIC GENERATION USING TWO-COLOUR LASER FIELDS

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The interaction between a strong laser field and an atomic or molecular gas can lead to the emission of coherent radiation in the XUV or x-ray region. This process, known as high harmonic generation (HHG), is leading to the development of table top, high flux XUV or x-ray sources that are invaluable tools in many areas of ultrafast physics. However, the very low conversion efficiency from the near or mid-IR laser fields to the short wavelength HHG light poses a significant limitation for the development of these XUV sources. We show that the use of a two-colour driving field can lead to a considerable enhancement of the HHG efficiency. Using a tunable mid-IR (1300-1600 nm) source as a driving field and an 800 nm source as an assisting field, the enhancement occurs only when the two fields have mutually orthogonal polarizations. The effect appears to be general and has been observed in a number of atomic and molecular systems.

HOW TO CONTROL ATOM-CHIP COHERENT DYNAMICS

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Controlling the coherent dynamics of a quantum system is an extremely useful but very challenging task, especially in presence of decoherence processes. Here we theoretically and experimentally apply different techniques to successfully perform it on a Rubidium atom-chip Bose-Einstein condensate. First of all, we show how to exploit the back action of quantum measurements and strong couplings to tailor and protect the coherent evolution of a quantum system inside a two-level subspace (quantum Zeno dynamics). Secondly, optimal control strategies are experimentally applied to realize high-fidelity state preparation and to drive forth and back the system through several paths in its five-level Hilbert space. These results are important steps forward in protecting and controlling quantum dynamics, e.g. enhancing atom interferometry sensitivity, and, broadly speaking, in testing new tools for quantum information processing.

[1] F. Schafer et al., Nature Communications **5**, 3194 (2014).

[2] C. Lovecchio et al., paper in preparation (2014).

[3] F. Caruso et al., paper in preparation (2014).

CREATING AND CONTROLLING OSCILLATING MOLECULAR DIPOLES UNDER STRONG FIELDS

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We consider the entanglement properties of a generalized symmetrical spin-1/2 diamond chain with various competing interactions. The system can be used for description of the natural mineral azurite ($Cu_3(CO_3)_2(OH)_2$). Since the rigorous theoretical treatment of geometrically frustrated quantum Heisenberg model is unattainable, we adopt the approximation of the Ising-Heisenberg diamond chain model. The latter introduces Ising spins at the nodal sites and the Heisenberg dimers on the interstitial decorating sites of the chain. Because of the separable nature of the Ising-type exchange interactions between neighboring Heisenberg dimers, calculation of the entanglement can be performed separately for each of them. For quantifying the thermal entanglement of the system we use the concurrence. Note that despite the long-standing interest towards the properties of the mineral azurite, the question of the type and strength of interactions between the Cu^{2+} ions is still open. Thus, a detailed analysis of the phase structure of the system in a wide range of exchange interaction strengths is strongly motivated. Particularly, we reveal various regimes, depending on the relation between competing interaction strengths, with different values of ground state entanglement. Finally, some novel effects, such as the two-peak behavior of concurrence versus temperature and coexistence of phases with different values of magnetic entanglement, are pointed out.

ROTATIONAL COOLING OF COULOMB-CRYSTALLIZED MOLECULAR IONS BY A HELIUM BUFFER GAS

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In this talk, I will discuss recent experimental results on helium buffer-gas cooling of the rotational degrees of freedom of MgH+ molecular ions, which are trapped and sympathetically crystallized in a linear radio-frequency quadrupole trap [1]. With helium collision rates of only 10 s^{-1}, i.e. four to five orders of magnitude lower than in usual buffer gas cooling settings, we have cooled a single molecular ion to an unprecedented measured low rotational temperature of 7.5 K. In addition, by only varying the shape and/or the number of atomic and molecular ions in larger Coulomb crystals, we have tuned the effective rotational temperature from 7 K up to 60 K by changing the micromotion energy. The very low helium collision rate may potentially even allow for sympathetic sideband cooling of single molecular ions, and eventually make quantum-logic spectroscopy of buffer gas cooled molecular ions feasible. Furthermore, application of the presented cooling scheme to complex molecular ions should have the potential of single or few-state manipulations of individual molecules of biochemical interest. This latter perspective can hopefully be exploited to disentangle various processes happening in complex molecules, like light harvesting complexes.

[1] A. K. Hansen, O. O. Versolato, S. B. Kristensen, A. Gingell, M. Schwarz, A. Windberger, J. Ullrich, J. R. Crespo Lpez-Urrutia and M. Drewsen, Nature vol. **508**, 76 (2014).

DRESSED-UP FOR QUANTUM TECHNOLOGY

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Cold atoms can be “dressed” with radio-frequency and microwave radiation resulting in applications to sensing, metrology and interferometry. The wide range of applications is due to the flexibility inherent in the vector coupling of a magnetic dipole moment to EM fields which can be varied in time, frequency, orientation and space. This talk will introduce the concept of the dressed atom, and present both old and new designs of ring traps [1,2] and race tracks [3].

[1] O. Morizot, Y. Colombe, V. Lorent, H. Perrin, and B. M. Garraway, Phys. Rev. A **74**, 023617 (2006).

[2] M. Vangeleyn, B. M. Garraway, H. Perrin, A. S. Arnold, J. Phys. B **47**, 071001 (2014).

[3] G. Sinuco-Leon, K. Burrows, A. S. Arnold, and B. M. Garraway, arXiv:1401.6796.

COHERENCE EFFECTS IN COLD RUBIDIUM ATOMS

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We report on our experiments on nonlinear magneto-optical effects in laser-cooled, near-degenerate rubidium samples. Atoms are laser-cooled and subsequently transferred to the crossed-beam optical dipole trap (ODT), formed by focusing of 1070-nm laser beams. The tight confinement of atoms enables magnetic field probing with a high spatial resolution of a few tens of micrometers. Interaction of atoms with a near-resonant, linearly polarized light leads to an effective creation of long-lived ground-state Zeeman coherences, which is observed through the nonlinear Faraday effect or free induction decay (FID) signals of the Larmor precession. Our experiments show that high rotation angles of a few degrees and coherence lifetimes of a few milliseconds can be achieved with cold atoms released from the magneto-optical trap (MOT). Moreover, we are able to optically detect the weak rf (kHz regime) magnetic fields. Application of these effects to precision magnetometry and its potential limits are presented. By employing the amplitude-modulation of the laser beam, for instance, we are able to measure high (geophysical range) magnetic fields. The presented work describes the experiments with a far off-resonant ODT, which enables much longer observation times. Our goal is to study coherence effects in the temperatures down to the limit of quantum degeneracy, i.e., a Bose-Einstein condensate and with the sensitivity close to the photonic-shot noise limit.

EFFICIENT AND BROADBAND FREQUENCY GENERATION BY COMPOSITE CRYSTALS

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Composite pulse sequences have been used for several decades in nuclear magnetic resonance and, since recently, in quantum information processing as a versatile control tool. In addition, novel universal broadband composite pulses have been introduced recently that perform robust population transfer and compensate errors in any experimental parameter for any pulse shape [1]. An important application of these sequences has been efficient and robust rephasing of atomic coherences in doped solids, which has also been verified experimentally [1].

We introduce another interesting application that uses an analogy with the universal composite pulses: composite crystals for efficient broadband sum and difference frequency generation [2]. This technique delivers high efficiency and robustness to parameter variations, e.g. when the phase matching condition is not fulfilled. It is a viable alternative to the adiabatic approaches because it requires much lower input intensity and shorter nonlinear crystals. It also works both with continuous-wave and pulsed lasers, as well as in the linear and nonlinear regimes of depleted and undepleted pumps, respectively.

[1] G. T. Genov, D. Schraft, T. Halfmann, N. V. Vitanov, arXiv:1403.1201.

[2] G. T. Genov, A. A. Rangelov, N. V. Vitanov, J. Opt. **16** 062001 (2014).

QUANTUM STATISTICS OF LIGHT TRANSMITTED THROUGH AN INTRACAVITY RYDBERG MEDIUM

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We theoretically investigate the quantum statistical properties of light transmitted through an atomic medium with strong optical non-linearity induced by Rydberg-Rydberg van der Waals interactions. In our setup, atoms are located in a cavity and non-resonantly driven on a two-photon transition from their ground state to a Rydberg level via an intermediate state by the combination of the weak signal field and a strong control beam. To characterize the transmitted light we compute the second-order correlation function $g^{(2)}(\tau)$. The simulations we obtained on the specific case of rubidium atoms suggest that the bunched or antibunched nature of the outgoing beam can be chosen at will by appropriately tuning the physical parameters.

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

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The control of quantum systems by external fields (such as laser and cavity) 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 that can feature photonic [1], atomic [2], molecular [3], and combined (dressed) states [4].

One of the most challenging issues 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. We present techniques that allow the design of fields for such a robust control, ranging from ultrafast adiabatic methods [5] to single-shot shaped pulses [6] and composite pulses [7].

Its extension to non-linear quantum systems, such as the one featuring the creation of molecular Bose-Einstein condensates from atomic ones, is shown [8].

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

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

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

[4] S. Guérin and H.R. Jauslin, Adv. Chem. Phys. **125**, 147 (2003).

[5] G. Dridi, S. Guérin, V. Hakobyan, H.R. Jauslin, and H. Eleuch, Phys. Rev. A **80**, 043408 (2009); S. Guérin, V. Hakobyan, and H.R. Jauslin, ibid **84**, 013423 (2011).

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

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

[8] S. Guérin, M. Gevorgyan, C. Leroy, H.R. Jauslin, and A. Ishkhanyan, Phys. Rev. A **88**, 063622 (2013).

STORING IMAGES UP TO ONE MINUTE BY EIT IN A DOPED SOLID

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Coherent light-matter interactions provide powerful tools to control optical properties in quantum systems, e.g. aiming at efficient optical storage (as required in quantum processing). The talk presents implementations of coherent optical interactions in particular solids, i.e. rare-earth doped crystals. The latter media combine the advantages of gases (i.e. spectrally narrow transitions) and solids (i.e. large storage density and scalability). In particular, the talk reports on applications of electromagnetically induced transparency (EIT) to store light pulses and images in atomic coherences in a conventional doped crystal (Pr:YSO). We demonstrate efficient operation of the solid memory by combination of EIT and image storage with feedback-controlled pulse shaping/evolutionary algorithms for enhanced optical preparation, angular and frequency multiplexing for enlarged storage capacity, as well as control strategies to beat decoherence. Combination of the powerful approaches permits prolongation of storage times in the EIT-driven solid memory up to the regime of one minute [1].

[1] G. Heinze, C. Hubrich, and T. Halfmann, Phys. Rev. Lett. **111**, 033601 (2013).

REPHASING OF SINGLE SPIN EXCITATIONS FOR TEMPORALLY MULTIPLEXED QUANTUM MEMORIES

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Future long-distance quantum communication networks critically rely on realistic quantum memories (QM) for light. Such devices allow coherent and reversible transfer of quantum information between flying qubits (typ. encoded in photons) and long-lived matter qubits (typ. encoded in atomic states).

An important benchmark for realistic QMs is the capability of temporal multiplexing, i.e. storing several qubits at the same time and selectively read them out afterwards. Although cold atomic ensembles provide excellent QMs, temporal multiplexed storage of single photons has not been achieved in these systems yet. We now demonstrate a significant step towards this goal.

In our experiment, we apply laser cooled Rubidium atoms, to form a QM based on the DLCZ-scheme. An incoming photon creates a single collective spin excitation via a Raman transition. The scattered photon is then used to indicate the charged QM. After the storage time, the QM can be read out by the inverse Raman process. To obtain the temporal multiplexing capability, we combine the DLCZ-memory with an externally controlled inhomogeneous broadening of the spin transition. By inverting the sign of the broadening, spin excitations which were stored at differing times will rephase at corresponding times after the switching point. This enables creation, storage and selective readout of single collective excitations in different temporal modes within the same atomic ensemble.

EXPERIMENTAL QUANTUM COMPUTATIONS ON A TOPOLOGICALLY ENCODED QUBIT

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The construction of a quantum computer remains a fundamental scientific and technological challenge, in particular due to unavoidable noise. Quantum states and operations can be protected from errors using protocols for fault-tolerant quantum computing (FTQC). Here we present a step towards this by implementing a quantum error correcting code, encoding one qubit in entangled states distributed over 7 trapped-ion qubits. We demonstrate the capability of the code to detect one bit flip, phase flip or a combined error of both, regardless on which of the qubits they occur. Furthermore, we apply combinations of the entire set of logical single-qubit Clifford gates on the encoded qubit to explore its computational capabilities. The implemented 7-qubit code is the first realization of a complete Calderbank-Shor-Steane (CSS) code and constitutes a central building block for FTQC schemes based on concatenated elementary quantum codes. It also represents the smallest fully functional instance of the color code, opening a route towards topological FTQC.

MICROWAVE QUANTUM LOGIC AND ARCHITECTURES FOR QUANTUM TECHNOLOGY WITH IONS

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To this point, entanglement operations on ion qubits have predominantly been performed using lasers. When scaling to larger qubit numbers however this becomes problematic due to the challenging engineering that might be required. The use of microwaves combined with a static magnetic field gradient overcomes this problem. I will present our work towards implementing entanglement gates using microwave radiation including the experimental demonstration of Schrödinger cat states and the first realisation of driving motional sideband transitions with microwave dressed states. I will also present our work creating microfabricated ion trap architectures for quantum simulation and quantum computation.

FEEDBACK-ENHANCED SPATIAL ORGANIZATION OF BOSE-EINSTEIN CONDENSATE IN AN OPTICAL LATTICE

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We consider a Bose-Einstein condensate placed in an optical lattice potential with the lattice depth controlled by a feedback loop. The control signal for the loop is the backward Bragg scattering of a weak probe light. The wavelength of the probe light is equal to the double period of the lattice. Under this condition the maximum Bragg scattering is obtained if the condensate wavefunction represents narrow peaks localized near the center of each lattice site. The feedback loop is designed to increase the lattice potential as the Bragg scattering increases, making the periodically localized condensate wavefunction more favorable. We assume that the probe and the scattered light are counterpropagating modes of a ring cavity, since the scattered signal is expected to be small and should be collected. The time response of the system due to the cavity is analyzed. We perform quantum analysis of the system using the formalism of the positive P-representation. We show that there is no additional quantum noise introduced into the system via the feedback loop, which is considered as an incoherent (containing measurement) electronic feedback. Solving numerically the stochastic differential equations derived from the positive P-representation Fokker-Planck equation we determine the effect of the quantum correlations between the scattered light and the condensate. The quantum statistical properties of the light and the condensate are found as well.

QUANTUM SIMULATION OF SUPEREXCHANGE MAGNETISM IN LINEAR ION CRYSTAL

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We present a system for the simulation of Heisenberg models with spins $s = \frac{1}{2}$ and $s = 1$ with a linear crystal of trapped ions. We show that the laser-ion interaction induces a Jaynes-Cummings-Hubbard interaction between the atomic V-type level structure and the two phonon species. In the strong-coupling regime the collective atom and phonon excitations become localized at each lattice site and form an effective spin system with varying length. We show that the quantum-mechanical superexchange interaction caused the the second-order phonon hopping processes creates a Heisenberg-type coupling between the individual spins. Trapped ions allow to control the superechange interactions by adjusting the trapping frequencies, the laser interansity, and the detuning.

QUANTUM FOURIER TRANSFORM WITH TRAPPED IONS

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We will present a simplified method for the implementation of the quantum Fourier transform (QFT) with trapped ions in a magnetic field gradient. Instead of the two-qubit c-phase gates, we use free evolution to entangle the qubits. An N-dimensional QFT matrix is produced with a series of $2N$ resonant pulses separated by proper time delays, as opposed to $O(N^2)$ as in standard proposals.

FEEDBACK COOLING OF THERMAL ATOMS USING BRAGG SCATTERING

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The new method of cooling and spatial organization of polarizable particles in a periodic light potential is proposed and theoretically justified. It is based on the detection of Bragg reflected light as an error signal for a feedback loop. It has been inspired by the cavity self-organization of atoms. The principal difference from the cavity self-organization is that instead of optical feedback mediated by the cavity we propose to use an electronic feedback that is more flexible and controllable by currently available facilities. Unlike in the systems such as collective atomic recoil lasers, we assume that the probe light is extremely weakly coupled to the atoms and there is no kick of atoms due to the probe light scattering. Nevertheless we show that the scattered light can be used in an electronic feedback loop to control additional potential and finally to cool the atoms. The role of the additional potential can be played by strong lasers forming an optical lattice. The simulation model is simplified to omit all quantum effects for both external and internal degrees of freedom of the atoms. The numerical analysis with realistic parameters has shown the possibility to reach the regime where the atoms get localized in the wells of the periodic potential simultaneously losing their kinetic energy. This is the threshold process with respect to the feedback gain. The timescale of the cooling process was shown to be comparable to the trapping time in conventional dipole traps.

ADIABATIC CONTROL OF NONLINEAR QUANTUM SYSTEMS; APPLICATIONS TO MOLECULAR BOSE-EINSTEIN CONDENSATES

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We analyze strategies for adiabatic control of nonlinear quantum systems by laser fields. We consider in particular the generation of molecular Bose-Einstein condensates (BEC) by photo-association of an atomic BEC. We will discuss some basic tools, like the relation between classical and quantum adiabatic theorems, resonant normal forms and crossings of separatrices and their higher dimensional generalizations. This work is made in collaboration with M. Gevorgyan, A. Ishkhanyan (IPR Ashtarak, Armenia), C. Leroy and S. Guèrin (ICB, Dijon, France).

PECULIARITIES OF BRIGHT AND DARK STATES FORMATION IN 3D3/2 AND 5D5/2 NA STATES

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We discuss the formation of bright and dark states in a generalized ladder scheme of three hyperfine manifolds upon coupling by a strong laser field. We investigate theoretically two excitation schemes, where a weak probe field is used in the first excitation step between the 3S1/2 and 3P3/2 states, while the strong field further couples the 3P3/2 to the 3D3/2 (or 3D5/2) states in Na. The population of the final state in the ladder scheme is investigated numerically as a function of the weak probe field detuning under different coupling field parameters, e.g. detunings and intensities. Depending on the number of the involved hyperfine levels, the coupling by a sufficiently strong laser field leads to the formation of only bright or bright and dark states. In the 3D3/2 case the intensities of the outermost bright peaks diminish until their full disappearance with sufficiently strong coupling field, while in the 3D5/2 case the intermediate bright states disappear and the outermost ones survive. This observation is confirmed by calculations of the dressed-states eigenvalues which match the positions of the bright and dark peaks.

CODING OF QUBITS, QUTRITS AND QUQUADS IN CAVITY-QED PHOTONS

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Photons acting as flying information carriers are key to many modern applications of quantum technology like, e.g., linear optics quantum computing (LOQC) and long-distance quantum communication. The arbitrary control of the photonic states in space and time is crucial to the success of these schemes. To this end, we have been developing new methods for the interfacing of atoms and photons in a cavity-qed, which allow for full quantum control of photon emission and absorption. In particular, we are using a vacuum-stimulated Raman process to control the spatio-temporal properties of single photons to an unprecedented degree, which allows us to obtain photons of arbitrary shape. We have been demonstrating the singleness and indistinguishability of these photons in sophisticated photon-photon correlation experiments, and we also achieved a single-photon production efficiency of 85% at a repetition rate of 1 MHz. Over and above that, we have been using this scheme to encode arbitrary qubits, qutrits and even ququads within the spatio-temporal mode profile of individual photons. The fidelity of this technique has been verified in time resolved quantum-homodyne measurements to be better than 96%. Such a close-to-perfect control of photonic wavefunctions might well change the way we think about quantum logic today. For instance, when using qutrits or ququads, powerful ternary or quaternary quantum logic concepts can be realised without the need for additional resources.

NONCLASSICAL STATE PREPARATIONS BY RESERVOIR ENGINEERING IN AN ION TRAP

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Coupling a quantum system to an engineered reservoir provides new opportunities for quantum state preparations, and for studying the dynamics of open quantum systems. In an ion trap, we can form engineered reservoirs because we precisely control interactions between the ion itself and the electromagnetic vacuum. We have recently demonstrated reservoir engineering of the motional states of a single calcium ion, realizing nonclassical states of the motion such as squeezed and coherent states as the steady-state of the dynamics. The spin-motion coupling utilizes a multichromatic laser field, producing jump operators in an engineered motional basis, which for us are the displaced and squeezed

Fock states. Taking advantage of this engineered coupling, we have demonstrated novel methods for state diagnosis and control working directly in the engineered eigenstate basis. The steady-state dissipative motion may also be used as an environment for further quantum systems, or for investigating many-body dissipative dynamics. I will describe how we plan to use two-species ion chains to investigate open systems using these methods, and will describe experimental progress towards this goal.

WITNESSING ENTANGLEMENT IN HYBRID SYSTEMS

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We extend the definition of entanglement witnesses based on structure factors to the case in which the position of the scatterers is quantized. This allows us to study entanglement detection in hybrid systems. We consider several examples showing how these extra degrees of freedom affect entanglement detection by directly contributing to the measurement statistics. We specialize the proposed witness operator to trapped ion crystals. Within this framework, we show how the collective vibronic state of the ions can act as an undesired quantum environment and how the ions motion can affect the entanglement detection. Finally, we investigate some specific cases where the method proposed leads to detection of hybrid entanglement.

QUANTUM STORAGE OF HERALDED SINGLE PHOTONS IN A PR BASED SOLID-STATE MEMORY

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Crystalline insulators doped with rare earth ions are promising systems for the realization of quantum memories, core elements in the architecture of quantum repeaters. Despite the extraordinary properties of Pr:YSO, including high efficiency [1] and long storage times [2], the storage of quantum light has never been achieved in this material. In fact, the hyperfine separation of the excited state establishes a tight bound to the bandwidth of the single photons to be stored (< 4 MHz). We report on the reversible mapping of heralded single photons to long lived collective optical excitation in Pr:YSO using the atomic frequency comb protocol [3]. The ultra-narrow band photons resonant with the memory are created by cavity-enhanced spontaneous parametric down-conversion and heralded by the detection of photons at the telecom wavelength [4]. We demonstrate quantum correlation between the retrieved and the heralding photons up to storage times of 4.5 us, more than 20 times longer than previous realizations with solid state systems [5]. Pr possesses an energy level scheme which allows the transfer to the ground state. However, the closely spaced hyperfine levels of the ground state (10.2 MHz) make the filtering of the technical excess noise introduced by the strong transferring pulses challenging. Adopting a narrow filtering strategy based on hole burning in a second Pr:YSO crystal, the spin-wave storage of weak coherent pulses, with an average number of photons per pulse lower than one, has been demonstrated for the first time.

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SOLID-STATE, HIGH POWER, TUNABLE CW LASER SYSTEM FOR QUANTUM OPTICS APPLICATIONS

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We present a compact all-solid-state laser system based on an optical parametric oscillator (OPO), pumped by a fiber laser, extended by intra-cavity sum frequency generation (SFG) and frequency stabilization, to provide intense radiation in the visible spectral regime [1]. The setup is based on a commercially available cw OPO system for mid-infrared output. The SFG and OPO processes are driven on a single periodically-poled lithium niobate crystal. Variation of the poling periods on the crystal allows for coarse wavelength tuning in a range between 605 and 616 nm. Pump wavelength tuning achieves a single-longitudinal mode tuning range of around 20 GHz. The robust, combined SFG-OPO approach is also applicable to other wavelength regimes. The system provides more than 1W output power over the full spectral range. A Pound-Drever-Hall frequency stabilization reduces the laser linewidth to the regime of 100 kHz (FWHM).

We apply the system for coherent, optical data storage in rare-earth doped solids, driven at a wavelength of 606 nm – which otherwise is only accessible by dye lasers or larger setups for frequency mixing of two phase-locked lasers. As a demonstration, the talk presents data on storage of light pulses in atomic frequency combs, driven by the SFG-OPO system in a Pr:YSO crystal.

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QUANTUM-LIKE PHENOMENA AND NONLINEAR OPTICAL FREQUENCY CONVERSION IN COUPLED WAVEGUIDES

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The equations governing the evanescent coupling of light between dielectric optical waveguides present a formal analogy with the Schrödinger equation describing the quantum population dynamics among coupled quantum levels in the rotating wave approximation. These analogies are inspiring increasing interest in fundamental studies as well as for potential applications in integrated optics. We will first summarize our recent studies in this context, for which we employ an experimental platform permitting the photo-inscription of reconfigurable waveguides. The attention will be focused on our recent investigations on waveguide structures with waveguide propagation constant evolving along the longitudinal propagation direction, which permit to verify the analogy to phenomena such as the two-state Stimulated-Raman Adiabatic Passage (two-state STIRAP). Coupled waveguides hold interest also for applications in nonlinear frequency conversion. Specifically, the back-and-forth bouncing of light between two waveguides allows in principle to realize a wealth of new phase-matching conditions for different types of nonlinear optical interactions. The second part of the talk will illustrate the theoretical framework that we have recently developed for such very rich phenomena, that we have called "Coupling Length Phase Matching" (CLPM). Illustrating examples for sum- and difference-frequency generation, second-harmonic generation, as well as third-order type three-wave interactions will be given.

GENERATION OF ENTANGLED PHOTONS IN NONLINEAR ADIABATIC WAVEGUIDING STRUCTURES

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We present a novel integrated scheme for the generation of Bell states, which allows simultaneous spatial filtering of pump photons. It is achieved through spontaneous parametric down-conversion in the system of nonlinear adiabatically coupled waveguides. We also demonstrate that the adiabatic couplers open the possibility to maintain the purity of generated Bell states in a relatively fabrication-fault-tolerant way.

PREPARATION OF AN ULTRACOLD MEDIUM AT EXTREME OPTICAL DEPTH

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Engineering strong coupling between individual photons at the few-photon level has been a long-standing goal in quantum optics. Strong coupling between photons enables single-photon switches and phase gates for quantum information processing and, e.g., also allows the generation of strongly correlated many-body photonic systems. Interactions between photons are always mediated by a medium. Strong coupling is achieved, e.g., by placing atoms into high-Q micro-cavities, harnessing dipole-dipole interactions between Rydberg atoms, or coupling the light fields to atomic ensembles. In the latter approach, the coupling strength is determined by the opaqueness of the ensemble, i.e., the optical depth (OD). In recent years, several experiments were proposed aiming at the all-optical generation of strongly correlated photonic systems, based on narrow-band electromagnetically induced transparency (EIT) in media of extreme OD beyond 1000. Such extreme ODs are typically not in reach with, e.g., laser-cooled atoms in magneto-optical traps. A promising approach towards extreme ODs is based on loading hollow-core fibers with atoms [1-5]. Here, light and atoms can be tightly confined over a macroscopic distance. In this talk, we will present our recent experimental results on loading laser-cooled rubidium atoms from a magneto-optical trap into the few micron-sized core of a hollow-core photonic crystal fiber [5]. By applying an optical dipole trap inside the fiber, we prevent collisions of the cold atoms with the room-temperature fiber wall. Via comparison of spectroscopic measurements and a calculation we determine the OD of our fiber-based medium as 1000. This represents the highest OD observed so far with cold atoms on a transition relevant to EIT and sets the basis for future experiments on strongly-correlated photonic systems.

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SOME FUNDAMENTAL ASPECTS AND APPLICATIONS OF NON-MARKOVIAN QUANTUM DYNAMICS

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Non-Markovian quantum dynamics and memory effects have recently attracted quite a large amount of attention both from fundamental and applicative perspective. We begin by recalling the concept of nonlocal memory effects [1] and show how this can be used to perform efficient teleportation with mixed states [2] and to protect a polarization entangled photon pair against decoherence when distributed in optical fibers [3]. From a more fundamental point of view, we discuss the universality of quantum memory effects [4] and conclude by presenting some schemes for discrete non-Markovian quantum walks implemented with photons.

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THREE-BODY FORSTER RESONANCES IN FROZEN RYDBERG GASES

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In frozen Rydberg gases, efficient long-range dipole-dipole interactions can lead to efficient transfer of population by exchange of internal energy between two Rydberg atoms. These Forster resonances can be matched by adding a small static electric field for shifting the Rydberg levels. They can be generalized to the case of a few Rydberg atoms. We will present the case of three atoms in the case of cesium.

ROBUST AND BROADBAND FREQUENCY CONVERSION IN NONLINEAR COMPOSITE CRYSTALS

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We propose an efficient, robust and broadband nonlinear optical frequency con-

version technique, which uses segmented crystals constructed in analogy with the composite pulses in nuclear magnetic resonance and quantum optics. The composite crystals are made of several macroscopic segments of nonlinear susceptibilities of opposite signs and specific thicknesses, which are determined from the condition to maximize the conversion efficiency with respect to variations in the experimental parameters. These crystals deliver broadband operation for significantly lower pump intensities than single bulk crystals. We demonstrate this technique by numerical simulation of sum frequency generation in MgO:$LiNbO_3$ crystal [1].

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INCREASING SENSING RESOLUTION WITH ERROR CORRECTION

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The signal to noise ratio of quantum sensing protocols scales with the square root of the coherence time. Thus, increasing this time is a key goal in the field. By utilizing quantum error correction, I will present a novel way of prolonging such coherence times beyond the fundamental limits of current techniques. I will present an implementable sensing protocol that incorporates error correction, and discuss the characteristics of these protocols in different noise and measurement scenarios.

PRODUCTION OF PHOTON STATES USING Λ-ATOMS IN A CAVITY

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We analyse the system of Λ-atoms in a cavity QED of semi-transparent mirror and driven by laser fields. We derive effective models and connect concepts (photonic flux, input-output operators, photonic state) characterizing the propagation of the resulting leaking photons. We propose an atom-cavity non-resonant scheme for single- and 2-photon generation. The pulse shapes of outgoing single photons are tailored using a specifically designed driving field envelope. For the production of 2-photon states, two trapped atoms are used with two driving pulses. Their pulse shapes are characterized and it is shown that the multiphoton outgoing photonic states cannot be Fock states, since the photons are not generated strictly simultaneously.

UNIVERSAL COMPOSITE PULSES FOR REPHASING OF ATOMIC COHERENCES IN A DOPED SOLID

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Composite pulses (CP) have been used for decades in nuclear magnetic resonance, and since recently, also in quantum information processing as a powerful tool to drive excitation processes via robust pathways. The general idea of CP is to improve the performance of an excitation process driven by a single pulse, by applying a sequence of pulses with appropriately chosen phases. Usually these CP compensate fluctuations in a single experimental parameter only. Here we introduce universal CP [1] for robust system inversion, compensating variations in any experimental parameters (i.e. pulse amplitude, pulse duration, static detuning, etc.), and also operate independent of the pulse shape. We demonstrate the performance of universal CP by inversion of atomic coherences in a rare earth ion-doped solid (Pr:YSO). Such doped solids are an attractive medium to implement solid-state quantum memories. The media exhibit long decoherence times and small homogenous optical line width, while maintaining the advantages of solids, i.e. large density and scalability. Typically, these memories rely on atomic coherences, driven between inhomogeneously broadened levels. Hence, robust rephasing protocols are required to cope with dephasing. Our experimental data confirm improved robustness of universal CP, in comparison with standard π-pulses, with regard to variations in pulse area, static detuning, and different pulse shapes.

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EXACTLY SOLVABLE TWO-STATE QUANTUM MODEL FOR A PULSE OF HYPERBOLIC-TANGENT SHAPE

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We present an analytically exactly solvable two-state quantum model, in which the coupling has a hyperbolic-tangent temporal shape and the frequency detuning is constant. The exact solution is expressed in terms of associated Legendre functions. An interesting feature of this model is that the excitation probability does not vanish, except for zero pulse area or zero detuning; this feature

is attributed to the asymmetric pulse shape. Two limiting cases are considered. When the coupling rises very slowly, it is nearly linear and the tanh model reduces to the shark model introduced earlier. When the coupling rises very quickly, the tanh model reduces to the Rabi model, which assumes a rectangular pulse shape and hence a sudden switch on. Because of its practical significance, we have elaborated the asymptotics of the solution in the Rabi limit, and we have derived the next terms in the asymptotic expansion, which deliver the corrections to the amplitude and the phase of the Rabi oscillations due to the finite rise time of the coupling.

DETERMINISTIC ION SOURCE REALIZING NANOMETER RESOLUTION AND THERMODYNAMICS WITH TRAPPED IONS

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Novel ion trap geometries for deterministic high resolution ion implantation are presented which are obtained by highly efficient field calculation methods [1]. I will present our recent progress with a segmented ion trap with mK laser cooled ions which serves as a high resolution deterministic single ion source. It can operate with a huge range of sympathetically cooled ion species, isotopes or ionic molecules. We have deterministically extracted a predetermined number of ions on demand [2], moved the ions inside the trap [3] without exciting any motional quanta and reached extraction accuracies of less than 10 nm [4]. These results a first step in the realization of an atomic nano assembler, a novel device capable of placing an exactly defined number of atoms or molecules into solid state substrates with sub nano meter precision in depth and lateral position. The project is motivated by the quest for novel tailored solid state quantum materials generated by deterministic high resolution ion implantation. Ions can also be moved by heat realizing a heat engine scaled down to a single ion [5]. We propose driving the trapped ion in an Otto cycle, oscillating in a specially designed linear Paul trap and coupled to engineered laser reservoirs. We present detailed Monte Carlo simulations and the calculation of the efficiency of such single ion heat engine, exceeding the standard Carnot limit when employing a squeezed thermal reservoir [6]. Finally, I will discuss how ions can be moved in the radial direction performing the experimental investigation of the Kibble-Zurek mechanism, where control parameters are tailored such that a structural phase transition from a linear to a zigzag configuration of the crystal is crossed. Trapped ions serve here as a clean model system to investigate universal laws of defect formation when such transition is crossed fast and causally separated regions form. The amount of defects is predicted by the Kibble-Zurek mechanism. We have experimentally determined the universal scaling exponent for defect formation and confirm the scaling law for the inhomogeneous Kibble-

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COHERENT ELECTRONIC MOTION IN FEMTOSCALE: GENERATING GIANT MOLECULAR ANTENNAS

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Attophysics deals with electron dynamics. In this talk we propose different schemes that employ ultrafast (attosecond) pulses and/or static fields or low frequency pulses in order to create and manipulate oscillating electric dipoles in homonuclear diatomic cations. We argue that any working control mechanism needs i) to break the symmetry of the system and ii) to sustain highly correlated electronic and nuclear motion, thus pushing the period of oscillation of the dipoles from the electronic (attosecond) timescale to the nuclear (femtosecond) timescales.

Using reduced dimensionality models with regularized soft-core Coulomb potentials for the Hydrogen molecular cation we show that one can create dipoles as large as 40 Debyes oscillating in the far- infrared regime, that act as molecular antennas.

INTERFACING SINGLE IONS AND PHOTONS VIA CAVITY QED

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The complementary benefits of trapped ions and photons as carriers of quantum information make it appealing to interface them at the single quantum level. Single ions provide long storage times, high fidelity coherent control and efficient state readout, whereas single photons travel over a long distance with small decoherence. The need for coherently interfacing single ions and photons naturally leads to cavity QED with single ions, where an optical cavity with small mode volume is used to achieve quantum mechanical coupling between two systems.

At University of Sussex we are currently working on two distinct ion-cavity QED experiments. In one of them, a cavity collinear to the axis of a linear Paul trap is employed where a moderate ion-photon coupling is expected. The simultaneous couplings of multiple ions to the same cavity mode can be exploited, for example, for probabilistic generation of entanglement. A stronger coupling can be achieved by using a miniature fibre cavity. We have developed a novel endcap-type ion trap which tightly integrates a high finesse fibre cavity inside the electrodes [1]. This design significantly reduces possible disturbances to the trap caused by the fibres dielectric surfaces and as a result allows us to bring the fibres as close as 150 μm to the ion. We have fabricated fibre cavities which are stable over a wide range of cavity length up to a few hundred μm, so that they can be used in this endcap trap. With strong ion-photon coupling, a deterministic transfer of quantum states between ions and photons becomes possible. We present the current status and future prospects of the two experiments.

[1] H. Takahashi et al. , New J. Phys. **15**, 053011 (2013).

BOSONSAMPLING WITH CONTROLLABLE DISTINGUISHABILITY

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Photonic BosonSampling computers have inspired significant interest because they have the potential to solve computationally hard problems efficiently using only a few-dozen indistinguishable photons. However, their ability to outperform classical computers is currently limited by their tight error tolerance.

Whereas practical BosonSampling computation depends on the quality of the apparatus it is the photons distinguishability which is the fundamentally limiting source of error. Here we develop a method describing the transition probabilities of photons with arbitrary distinguishability through any linear-optical network. We test this experimentally by tuning the temporal delay of the input-photons. Our approach provides tighter estimates for the underlying BosonSampling distribution by relating the output to the transition matrix immanants, enabling the main source of errors to be quantified. This is essential for experimentally realizable implementations. Our method may enable generalized BosonSampling computation through the use of immanants and not just permanents.

IMPROVEMENT OF ADIABATICITY: COMPOSITE PULSES AND NON-HERMITIAN SHORTCUTS

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We study two different methods for the optimization of adiabatic passage in two and three-level systems. The first method is based on composite pulses and the second on non-Hermitian shortcuts to adiabaticity. The technique of composite pulses uses a sequence of pulses with relative phases, used as control parameters. This allows the nonadiabatic losses to be canceled to any desired order with sufficiently long sequences, regardless of the nonadiabatic coupling, by choosing the phases between the constituent pulses appropriately. This technique is applied for the improvement of the fidelity of rapid adiabatic passage (RAP) and stimulated Raman adiabatic passage (STIRAP). On the other hand, the method of shortcuts to adiabaticity allows the adiabatic processes, which are usually considered slow, to increase their speed. We achieve this by adding a non-Hermitian term in the Hamiltonian, which cancels exactly the nonadiabatic coupling. We show how this is applied in RAP and STIRAP.

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

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

[3] B. T. Torosov, G. Della Valle and S. Longhi, Phys. Rev. A **87**, 052502 (2013).

TOWARDS LASING WITHOUT INVERSION IN NEUTRAL MERCURY

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In this talk we present recent progress towards the implementation of a four-level lasing without inversion (LWI) scheme in mercury. It is based on theoretical calculations by Fry [1] and aims at demonstrating LWI based UV cw-lasers at 253.7 nm. Laser radiation of two lasers, both of which are at much longer wavelength than that of the LWI laser output, is required to set up the necessary coherence in a mercury filled gas cell. The particular alignment of the lasers enables compensation for the Doppler effect leading to high efficiency. During the talk we will present detailed numerical simulations concerning the experimental realization as well as the present status of the experiment.

[1] E. S. Fry, M. D. Lukin, Th. Walther, and G. R. Welch, Optics Communications, 179:0 499-504 (2000).

RECENT DEVELOPMENTS IN MULTIPHOTON PHOTOELECTRON CIRCULAR DICHROISM (PECD)

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PECD describes the asymmetry in the photoelectron angular distribution (PAD) after ionization of randomly oriented chiral molecules in the gas phase with circularly polarized light. PECD was observed in one photon ionization using synchrotron radiation. Recently, we have measured PECD by femtosecond REMPI of camphor and fenchone molecules [1]. In our experiments strong contributions of higher order Legendre polynomials were observed. To apply PECD as a sensitive analytical tool, quantitative measures to evaluate the experimental PECD data are required. For one photon ionization, parameters to characterize the asymmetry of the PAD based on the forward/ backward asymmetries have been developed [2]. Although this method can be extended to the multiphoton case, we show that measures based on the forward/backward asymmetry are generally not sufficient to quantify the multiphoton PECD. We suggest a more general measure based on the decomposition of the PAD into their gerade and ungerade part. In addition, a measure to evaluate images from noncylinder symmetrical PAD is introduced. These measures are evaluated on experimental multiphoton PECD data from camphor molecules.

[1] C. Lux et al., Angew Chem Int Ed **51**, 5001 (2012).

[2] L. Nahon et al., J Chem Phys **125**, 114309 (2006).

ADDRESSING A QUANTUM BYTE AND ROBUST DYNAMICAL DECOUPLING FOR CONDITIONAL QUANTUM GATES

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We report on recent experimental achievements using trapped $^{171}Yb^+$ ions that interact via Magnetic Gradient Induced Coupling (MAGIC).

The addressing of a particular qubit within a quantum register is a key prerequisite for scalable quantum computing. We demonstrate addressing of individual qubits within a quantum byte (eight qubits) and measure a crosstalk associated with the application of single-qubit gates on the order of 10^{-5}, breaching an important threshold for fault-tolerant quantum computing [1].

Dynamical decoupling (DD) sequences are applied to protect CNOT gates against decoherence. The sequences employed here are robust against imperfections of DD pulses that otherwise may destroy quantum information or interfere with gate dynamics. A CNOT gate is implemented, despite the gate time being more than one order of magnitude longer than the intrinsic coherence time of the system [2].

[1] Ch. Piltz, Th. Sriarunothai, A. Varon, and Ch. Wunderlich, arXiv:1403.8043.

[2] Ch. Piltz, B. Scharfenberger, A. Khromova, A. F. Varon, and Ch. Wunderlich, Phys. Rev. Lett. **110**, 200501 (2013).

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CAMEL X Programme

Time	Mon, 23	Tue, 24	Wed, 25	Thu, 26	Fri, 27
09:00-09:40	Wollenhaupt	Halfmann	Montemezzani	Pillet	Maniscalco
09:40-10:20	Bruner	Kuhn	Neshev	Walther	Piilo
10:20-10:50	coffee	coffee	coffee	coffee	coffee
10:50-11:30	Wunderlich	Drewsen	Singer	Jauslin	Gawlik
11:30-12:10	Hensinger	Hennrich	Retzker	Guérin	S. Ivanov P. Ivanov
12:10-12:40	Takahashi	Lo	Tillmann	Brion	Caruso
			trip (13:30-18:30)		
16:30	coffee	coffee		coffee	coffee
17:00-17:40	Peters	Garraway		Sola	Kirova Rousseaux
17:40-18:00	Bayer	Heinze		Chang	T. Ivanova
18:00-18:20	Braun	Mazzera		Grankin	D. Ivanov
18:20-18:40	Torosov	Schraft		Salo	Simeonov
18:40-19:00	Rangelov	Mieth			
19:00-19:20	Genov				
20:30				**conf. dinner**	

The workshop opens with a welcome drink on Sunday, June 22, at 20:00 in front of the lecture hall.