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

Hotel Sol Marina Palace, Nessebar, Bulgaria, June 19 – June 22, 2017

CAMEL XIII

Thirteenth International Workshop

BOOK OF ABSTRACTS

Edited by

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Noon Session chaired by **Thomas Busch**

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11:40-12:20 **Andreas Ruschhaupt**, *News about shortcuts to adiabaticity: spatial non-adiabatic passage*

12:20-12:40 **Tom Dowdall**, *Quantum coherent control via Pauli blocking*

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Evening Session chaired by **Thomas Walther**

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18:10-18:40 **Anne Cournol**, *Ro-vibrational cooling of molecules*

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09:40-10:20 **Matthias Wollenhaupt**, *Bichromatic control of multi-photon ionization*

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17:40-18:10 **Lachezar Simeonov**, *Generation of non-Abelian geometric phases in degenerate atomic transitions*

18:10-18:40 **Roberto Grimaudo**, *Quantum dynamics of two coupled spins under controllable and fluctuating magnetic fields*

18:40-19:00 **Kaloyan Zlatanov**, *Adiabatic generation of arbitrary coherent superpositions of two quantum states*

List of Abstracts

SINGLE ATOM EDGE-LIKE STATES VIA QUANTUM INTERFERENCE

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We demonstrate that quantum interference may lead to the generation of robust edge-like states (ELS) of a single ultracold atom in two-dimensional optical ribbons [1]. These states can be engineered either within the manifold of local ground states of the sites forming the ribbon, or of states carrying one unit of orbital angular momentum (OAM). First, we consider a system of three in-line sites and we show that in this system quantum interference effects give rise to spatial dark states (SDS). Then, by using the SDS as basic building blocks, global ELS can be created in arbitrarily large ribbons. These ELS are very robust against defects of the ribbon and perturbations in the phase differences between the local eigenstates of the sites. For the manifold of local ground states, quantum interference effects are solely due to phase differences in the local states of the sites, allowing to create ELS in a large variety of geometrical configurations. In addition, the different ELS could be coupled with laser pulses inducing oscillations between global eigenstates of the ribbon. In the case of states carrying one unit of OAM, quantum interference is due to complex tunneling amplitudes, whose phases are modulated by the relative orientation between sites [2] and we suggest to use the winding number associated to the angular momentum as a synthetic dimension.

[1] G. Pelegr et al., Phys. Rev. A **95**, 013614 (2017);
[2] J. Polo et al., Phys. Rev. A **93**, 033613 (2016).

OPTICAL COMMUNICATION IN THE LOW-POWER REGIME

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Quantum theory of electromagnetic radiation defines fundamental limits on the capacity of optical communication channels. Approaching the quantum limits requires a change of paradigm from measuring quantities well defined in classical systems, such as amplitude or phase, to exploiting quantum state distinguishability. These issues are especially pertinent in the regime of low signal power, which is currently explored e.g. for deep-space satellite communication at optical frequencies.

ROBUST ENHANCEMENT OF HIGH HARMONIC GENERATION VIA ATTOSECOND CONTROL OF IONIZATION

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Advancements in high harmonic generation (HHG) have led to the development of table-top XUV and soft X-ray light sources for attosecond science. However, the very low conversion efficiency of HHG, particularly for longer wavelength driving laser fields, poses a significant practical limitation for the use of these sources in many experimental applications. To compensate for the low single atom efficiency, phase matching methods are typically implemented in order to extend the effective generation length in the atomic medium. In this work, we demonstrate a different approach to optimizing HHG that enhances the single atom response to the driving laser field. We show that using a bichromatic driving field, subcycle control of the tunnel ionization dynamics can be achieved, leading to considerable enhancement of the ionization rate compared with a single colour field. Resultant increases in HHG efficiency by over two orders of magnitude have been observed. Our method offers a simple route toward scalable, robust XUV sources and the advancement of HHG spectroscopy, where isolating the single atom or molecule response is essential and exploiting phase matching schemes is not possible.

CONTROLLING SUPERFLUID FLOW IN BOSE-EINSTEIN CONDENSATES

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Superfluidity in Bose-Einstein condensates is a manifestation of long range correlations. Its hallmark is the existence of quantised vortices with their characteristic core and 1/r azimuthal velocity profile. However, other flow patterns in finite sized systems are possible, and in this presentation I will discuss two experimentally realistic examples.

In the first one I will show that the introduction of short range correlations into a superfluid system can lead to a dynamics that is reminiscent of classical rotation, where the velocity profile is directly proportional to the radius r. The required short-range correlations exist in two-component condensates and in the phase-separation regime they lead to radial flow in azimuthally symmetric potentials.

In the second example I will show how artificial gauge fields for neutral atoms can be used to create single vortex-rings and vortex-ring-lattices in a controlled manner. The basis for this is the presence of artificial gauge fields created by the optical near field potentials around optical nano fibers, which are highly tunable and allow to study the dynamics of vortex rings in many different situations.

RO-VIBRATIONAL COOLING OF MOLECULES

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Laser techniques applied to precision spectroscopy or to the control of internal and external degrees of freedom have considerably improved our knowledge on molecular physics. One of the greatest challenges of modern physical chemistry is to push forward the limits of electromagnetic and laser techniques to manipulate and probe molecules at low temperatures where molecular interactions are dominated by pure quantum phenomena.

In this context we have developed an original technique that enables us to manipulate the internal degrees of freedom of diatomic molecules. The principle consists in using broadband lasers to pump population of all the internal levels towards a target level. We have performed such technique on cesium dimers [1]. We apply this method to ro-vibrationally cool barium monofluoride (BaF) molecules produced in a supersonic beam. BaF is a good candidate as it has a suitable vibrational structure [2].

[1] I. Manai, R. Horchani, H. Lignier, P. Pillet, D. Comparat, A. Fioretti and M. Allegrini, Phys. Rev. Lett. **109**, 183001 (2012);

[2] C. Effantin, A. Bernard, J. d'Incan, G. Wannous, J. Verges and R. F. Barrow, Mol. Phys. **70**, 735-745 (1990).

REVERSE ENGINEERING CONTROL FOR MOLECULAR BOSE-EINSTEIN CONDENSATION

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In the second quantization formalism, the dynamics between condensed atoms and molecules is described by a Gross-Pitaevskii equation in the mean-field approximation. In this talk, we describe how to adapt the tools of control initially developed for linear quantum systems to nonlinear systems. We show in particular a method to shape the control fields of a *one-step nonlinear adiabatic passage* from free atoms to ground-state molecules (as early proposed in Ref [1] without specific shaping), instead of the usual (limited) two-step passage through the production of Feshbach molecules. This new method is efficient, robust and features a transient controlled (low) population in the lossy state. It is based on an exact solution of the nonlinear Schrödinger equation which is tracked by the actual dynamics via the control fields. The atom-molecule 2nd order nonlinearities are thus taken into account by the control.

In such molecular systems, 3rd order nonlinearities arise from the elastic collisions between species [2]. We describe how these effects, known as *mean-field shifts*, can be exactly dynamically compensated using time-dependent detunings. This method generalizes nonlinear adiabatic passage techniques [3,4] to exact passage.

[1] Mackie, M., Kowalski, R., Javanainen, J., Physical Review Letters, 84, 3803 (2000);

[2] Timmermans, E., Tommasini, P., Hussein, M., Kerman, A., Physics Reports, 315, 199-230 (1999);

[3] Guérin, S., Gevorgyan, M., Leroy, C., Jauslin, H. R., Ishkhanyan, A., Physical Review A, 88, 063622 (2013);

[4] Gevorgyan, M., Guérin, S., Leroy, C., Ishkhanyan, A., Jauslin, H. R., The European Physical Journal D, 70, 253 (2016).

QUANTUM COHERENT CONTROL VIA PAULI BLOCKING

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Coherent quantum control over many-particle quantum systems requires high fidelity dynamics. One way of achieving this is to use adiabatic schemes where the system follows an instantaneous eigenstate of the Hamiltonian over timescales that do not allow transitions to other states. This, however, makes control dynamics very slow. Here we introduce another concept that takes advantage of preventing unwanted transitions in fermionic systems by using Pauli blocking: excitations from a protected ground state to higher-lying states are avoided by adding a layer of buffer fermions, such that the protected fermions cannot make a transition to higher lying excited states because these are already occupied. This allows to speed-up adiabatic evolutions of the system. We do a thorough investigation of the technique, and demonstrate its power by applying it to high fidelity transport, trap expansion and splitting in ultracold atoms systems in anharmonic traps. Close analysis of these processes also leads to insights into the structure of the orthogonality catastrophe phenomenon.

DRESSED ADIABATIC TRAPS FOR COLD ATOMS: GOING BEYOND LANDAU-ZENER

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Dressing atoms with radio-frequency and microwave radiation opens up new possibilities for the adiabatic trapping of cold atoms and condensates in new topologies such as spherical surfaces, wave-guide loops [1,2] and (non-optical) lattices [3,4]. This is because of the flexibility inherent in the vector coupling of a magnetic dipole moment to electromagnetic fields which can be varied in time, frequency, orientation and space. This may in turn result in quantum technology applications to sensing (with ring traps and gyroscopes [5,6]), metrology, interferometry and atomtronics. This presentation will give a brief overview of the development of the field before focussing on our latest work on the application of the Landau-Zener model to the the adiabatic trapping problem [7]. It is found that, when carefully implemented, the Landau-Zener theory overestimates the rate of non-adiabatic spin flip transitions in the adiabatic limit. This indicates that care is needed when determining requirements for practical atom traps.

[1] B. M. Garraway and H. Perrin, J. Phys. B **49**, 172001 (2016);

[2] H. Perrin and B. M. Garraway, in Advances in Atomic, Molecular and Optical Physics, **66** (Academic Press, 2017), in press;

[3] G. A. Sinuco-Leon and B. M. Garraway, New J. Phys. **17**, 053037 (2015);

[4] G. A. Sinuco-Leon and B. M. Garraway, New J. Phys. 18, 035009 (2016);

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

[6] G. Sinuco-Leon, K. Burrows, A. S. Arnold, and B. M. Garraway, Nat. Commun. **5**, 5289 (2014);

[7] K. Burrows, B.M. Garraway and H. Perrin, arxiv:1705.00681, submitted (2017).

ARBITRARILY ACCURATE PULSE SEQUENCES FOR ROBUST DYNAMICAL DECOUPLING

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Quantum technologies are increasingly important nowadays for sensing, processing, and communication of information. However, protection of quantum systems from the environment remains a major challenge. Dynamical decoupling (DD) is a practical and widely used approach that aims to achieve this goal by applying sequences of pulses. Most DD schemes focus on dephasing processes due to their high contribution to data loss. Then, pulse imperfections remain the main challenge. Robust DD sequences have also been designed but most compensate errors in one or two parameters only (e.g., flip angle) or for a specific initial state. Ultra-high fidelity can potentially by achieved by nesting of sequences, but this requires an exponential growth in the number of pulses.

We introduce universally robust sequences for dynamical decoupling, which simultaneously compensate pulse imperfections and the detrimental effect of a dephasing environment to an *arbitrary* order, work with any pulse shape, and improve performance for any initial condition [1]. Moreover, the number of pulses in a sequence grows only linearly with the order of error compensation. Our sequences outperform the state-of-the-art robust DD sequences. Beyond the theoretical proposal, we also present convincing experimental data for dynamical decoupling of atomic coherences in a solid-state optical memory.

[1] G. T. Genov, D. Schraft, N. V. Vitanov, and T. Halfmann, Phys. Rev. Lett. **118**, 133202 (2017).

QUANTUM DYNAMICS OF TWO COUPLED SPINS UNDER CONTROLLABLE AND FLUCTUATING MAGNETIC FIELDS

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The quantum dynamics of two spins $\hat{\mathbf{j}}_1$ and $\hat{\mathbf{j}}_2$ (with values $j_1 \geq j_2$), subjected to external and controllable time-dependent magnetic fields and under a $\hat{\mathbf{J}}^2 = (\hat{\mathbf{j}}_1 + \hat{\mathbf{j}}_2)^2$-conserving bilinear coupling is investigated. Each eigenspace of $\hat{\mathbf{J}}^2$ is dynamically invariant and the Hamiltonian of the total system restricted to any one of such $(2j_2+1)$ eigenspaces, possesses the SU(2) structure of the Hamiltonian of a single fictitious spin acted upon by the given controllable magnetic field. We show that such a reducibility holds regardless of the time-dependence of the externally applied field as well as of the statistical properties of the Overhauser noise, here represented as a classical fluctuating magnetic field. Exploiting such a remarkable result, the time evolution of the joint transition probabilities of the two spins $\hat{\mathbf{j}}_1$ and $\hat{\mathbf{j}}_2$ between two prefixed factorized states is examined, bringing to light peculiar dynamical properties of the system under scrutiny. In particular, when the noise-induced non unitary dynamics of the two coupled spins is properly taken into account, the paper reports explicit analytical expressions for the joint Landau-Zener transition probabilities. The possibility of taking advantage of these exact results to envision a feedback-test on the reliability of the modelling adopted for unavoidable environmental effects in a given set-up, is finally briefly discussed.

INTERFACING DISPARATE QUANTUM MEMORY SYSTEMS FOR HYBRID QUANTUM OPTICS EXPERIMENTS

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The interconnection of fundamentally different quantum platforms via photons is a key requirement to build future hybrid quantum networks. Such heterogeneous architectures hold promise to offer more powerful capabilities than their homogeneous counterparts, as they would benefit from the individual strengths of different quantum matter systems.

We report on our recent experiments interfacing a cold atomic ensemble of Rubidium atoms operated as read-only quantum memory (QM) with two other very distinct quantum platforms. First, we demonstrate storage and retrieval of a paired single photon, emitted from the cold Rb QM, on a highly excited Rydberg state of a second, separate Rb ensemble via electromagnetically induced transparency. We show that nonclassical correlations between both photons persist after the storage and retrieval process. Second, we interface the paired single photon from the cold Rb QM with a rare-earth ion-doped solid state QM. As both systems exhibit very different optical transitions, we apply cascaded frequency conversion techniques to bridge the wavelength gap and moreover transmit the single photon at telecom wavelength which is favorable for long distance communication. We demonstrate that the coherence of the

single photon is preserved after frequency conversion and storage and retrieval from the solid state QM. Finally, we show qubit transfer between the two fundamentally different QM systems with fidelities surpassing the classical threshold.

COHERENT CONTROL OF TRAPPED RYDBERG IONS

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Trapped Rydberg ions are a novel quantum system [1]. By combining the high degree of control of trapped ion systems with the long-range dipole-dipole interactions of Rydberg atoms [2], fast entanglement gates may be realized in large ion crystals [3]. Quantum information processing in this system is envisaged to use low-lying electronic states for storage of qubits and strongly interacting Rydberg states for entanglement operations. This requires the Rydberg excitation to be coherently controlled. In our experiment [4] we have observed the first coherent Rydberg excitations of an ion via a two-photon excitation to Rydberg S states. Coherent effects observed include Rabi oscillations, EIT and STIRAP. We also report the realization of microwave-dressed Rydberg ions driving the transition between Rydberg S and P states. This marks an important step towards realizing entanglement operations between Rydberg ions, which are envisaged to strongly interact with each other via the large oscillating dipole moments of microwave-dressed Rydberg states.

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

[2] D. Jaksch, et al., Phys. Rev. Lett. **85**, 2208 (2000);

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

[4] G. Higgins, et al., arXiv:1611.02184v1 (2016).

CONSTRUCTING A MICROWAVE TRAPPED ION QUANTUM COMPUTER

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Trapped ions are a promising tool for building a large-scale quantum computer. The number of radiation fields (such as lasers) required for the realisation of quantum gates in any proposed ion-based architecture scales with the number of ions inside the quantum computer, posing a major challenge when imagining a device with millions of qubits. Here I present a fundamentally different approach [1], where this scaling entirely vanishes. The method is based on individually controlled voltages applied to each logic gate location to facilitate the actual gate operation analogous to a traditional transistor architecture within a classical computer processor. Instead of aligning numerous laser beams into designated entanglement zones, the use of a single microwave source outside the vacuum system is sufficient. We have demonstrated the key principle of this approach by implementing a two-qubit quantum gate based on long-wavelength radiation where we generate a maximally entangled two-qubit state with fidelity 0.985(12). I will also discuss the engineering blueprint for a large-scale microwave trapped-ion quantum computer we have recently released [2]. The work features a new invention permitting actual quantum bits to be transmitted between individual quantum computing modules using electric fields in order to obtain a fully modular large-scale machine. Finally I will introduce a powerful technique to transform existing two-level quantum control methods to new multi-level quantum control operations and illustrate the process using experiments with trapped ions.

[1] S. Weidt, J. Randall, S. C. Webster, K. Lake, A. E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker, and W. K. Hensinger, Phys. Rev. Lett. **117**, 220501 (2016);

[2] B. Lekitsch, S. Weidt, A.G. Fowler, K. Molmer, S.J. Devitt, Ch. Wunderlich, and W.K. Hensinger, Science Advances **3**, e1601540 (2017).

INTERFACING IONS AND PHOTONS

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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 travel 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 18 MHz with a cavity line width of 10 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. In another experiment, we combine a conventional cavity with a linear ion trap to facilitate the investigation of the interaction of multiple ions with a single cavity mode. We have demonstrated the localisation of several ions in a collinear cavity-trap system and have demonstrated the emission of polarised single photons from this system. To enable the use of fibre cavities in applications such as single photon sources and nodes in quantum networks the coupling between the cavity and the fibre must be significantly improved. 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

BOSON OR FERMION? QUANTUM CONFUSION WITH CAVITY PHOTONS

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We demonstrate quantum logic and quantum feedback using narrow linewidth photons that are produced with an a-priory non-probabilistic scheme from a single atom strongly coupled to a high-finesse cavity [1]. We use a controlled-NOT gate integrated into a photonic chip to entangle these photons [2], and we observe non-classical correlations between photon detection events separated by periods exceeding the travel time across the chip by three orders of magnitude. Furthermore we apply a quantum-feedback scheme in a two-photon interference setting that allows deliberate switching between bosonic and fermionic photon behaviour [3].

[1] A. Kuhn, Cavity Induced Interfacing of Atoms and Light, in Engineering the Atom-Photon Interaction, Springer (2015);

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

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

HARMONIC GENERATION IN GAS-FILLED WAVEGUIDES IN THE VICINITY OF MULTI-PHOTON RESONANCES

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Frequency conversion techniques extend the spectral region accessible by lasers from the mid-infrared towards soft x-rays. However, only gaseous media are applicable in the VUV and XUV, which reduces the conversion efficiency due to the low density in such media. Hollow-core optical waveguides permit spatial confinement of both the driving radiation as well as the medium. This provides long interaction length, while still maintaining phase-matching conditions. Tuning to multi-photon resonances offers another option to increase the nonlinear susceptibilities of the medium. We investigate phase-matched harmonic generation of ultrashort (ps) laser pulses, tuned in the vicinity of a five-photon resonance in Argon, confined in a capillary with a diameter of 100 μm. We study the dependence of the conversion efficiency, resonance shifts, and phase-matching conditions with gas pressure, driving fundamental wavelength, intensity, and admixture of buffer gas. We compare the experimental data with extended numerical simulations, taking higher spatial modes and cascade frequency conversion into account, identifying also the significant contribution of quasi-phase-matching by polarization beating. Our investigations show, that proper choice of experimental parameters enables significant resonance enhancements in the conversion efficiencies.

DYNAMICAL OPTICAL SIMULATOR FOR GENERIC DEPHASING

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We describe the progress of the theoretical and experimental work on developing an optical simulator for generic dephasing dynamics. The simulator system is the polarization of a single photon and its dynamics is induced by interaction with the frequency degree of freedom of the photon [1]. The total polarization frequency system

is prepared in specific correlated states to induce the desired dynamics. As an example dynamics to be simulated, we use the well-studied Loschmidt echo of a central spin coupled to an Ising chain in a transverse field [2]. To illustrate the versatility of the simulator, we have chosen to simulate the Loschmidt echo in three fundamentally different cases: below, above, and exactly at the critical value of the strength of the transverse field.

[1] B.H. Liu, L. Li, Y.F. Huang, C.F. Li, G.C. Guo, E.M. Laine, H.P. Breuer and J. Piilo, Nat. Phys. **7**, 931 (2011);
[2] P. Haikka, J. Goold, S. McEndoo, F. Plastina, and S. Maniscalco Phys. Rev. A **85**, 060101(R) (2012).

EFFECTIVE LANDAU-ZENER TRANSITIONS IN THE DYNAMICAL CASIMIR EFFECT

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Evaluating the dynamics of a circuit QED single-qubit driven by a time-dependent interaction modulated by a linearly varying frequency, it can be singled out that effective Landau-Zener processes are responsible for a significant photon production. To asses experimental feasibility, a Markovian quantum noise is considered and its effects are evaluated, also comparing different approaches.

QUANTUM INFORMATION PROCESSING AND METROLOGY WITH SINGLE ^{9}BE$^+$ IONS

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We present experiments with single 9Be$^+$ ions with applications in quantum information processing and metrology. In surface-electrode ion traps, we trap single 9Be$^+$ ions at an intermediate magnetic field strength where selected hyperfine states form a first order magnetic-field independent qubit for long coherence times. We discuss the design and operation of tailored near-field microwave waveguides embedded into the structure for full spin-motional control over these qubit states. We discuss applications of the near-field approach in quantum information processing and quantum many-body physics and present an extension of our trap fabrication capabilities to tailored, planarized and multi-layer structures. We further present ideas and concepts to use single 9Be$^+$ ions for sympathetic cooling and detection of (anti-)protons for precision measurements. We discuss a cryogenic Penning trap apparatus based on the BASE experiment to implement these ideas and present first experimental results on laser systems for controlling 9Be$^+$ at high magnetic field in a Penning trap, based on direct frequency comb control. We acknowledge funding by DFG through CRC1227 DQ-mat, projects A01 and B06 and ERC StG “QLEDS”. This project is part of and

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FAST THERMALIZATION OF A FROZEN RYDBERG GAS IN LONG-RANGE INTERATOMIC DIPOLE-DIPOLE COUPLING

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The long-range dipole-dipole interactions in a gas of cold atoms lead to numerous possible applications for instance the formation of ultra-cold molecules via the photoassociation of cold atoms, or the realization of scalable quantum gates via the dipole blockade of the Rydberg excitation, and the realization of Rydberg "crystals" again using the dipole blockade. The origin of such an interest is contained in the exaggerated properties of the Rydberg atoms, which can acquire huge electric momentum scaling up to n^2 in atomic units, meaning a few thousand times those of very polar molecules. Today the accurate control of such interatomic interactions in ultracold gases or quantum gases opens the way to a very active research field in quantum simulation, where the frozen Rydberg atoms permit one, the realization of many physical configurations, mimicking problems in condensed matter physics.

We consider here the case of a cold, disordered and dense cesium Rydberg gas in a configuration of resonance of Foerster [1,2], where two atoms or a group of atoms exchange internal energy by a resonant way. We will discuss the case of the two-body Foerster resonance, and we introduce the one of three-body Foerster resonance, also qualified as Borromean [3] because occurring in the absence of any effect due two-body Foerster resonances. In the case of the two-body Foerster resonance, we can reach the saturation regime, characterized by a quite amazing behavior corresponding to the "thermalization" of the atomic sample, meaning an equal- distribution of the populations of the relevant level of the resonance. The dynamics of the thermalization seems to be the result of few-body effects. The interplay between two-, few- [3,4] and many-body regime in a dipole coupling dense frozen Rydberg gas will be discussed.

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[3] R. Faoro, B. Pelle, A. Zuliani, P. Cheinet, E. Arimondo, P. Pillet, Nature Communications **6**, 8173 (2015);

[4] J.H. Gurian, P. Cheinet, P. Huillery, A. Fioretti, J. Zhao, P.L. Gould, D. Comparat, P. Pillet, Phys Rev. Lett. **108**, 023005 (2012).

REMOTE POLARIZATION ENTANGLEMENT GENERATION BY LOCAL DEPHASING AND FREQUENCY UPCONVERSION

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Photons have recently been used to simulate open system dynamics and to control non-Markovian memory effects in their dynamics. This has also allowed the realization of non-local memory effects and their exploitation in superdense coding. In the current work we exploit initial frequency entanglement between the photons and show theoretically how this can be converted to their polarization entanglement by local processes only. This opens the possibility, e.g., to prepare polarization entanglement remotely by using local dephasing processes and also to detect frequency entanglement by polarization measurements.

SUB-MILLIHERZ MAGNETIC SPECTROSCOPY WITH A NANOSCALE QUANTUM SENSOR

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Precise timekeeping is critical to metrology, forming the basis by which standards of time, length and fundamental constants are determined. Stable clocks are particularly valuable in spectroscopy as they define the ultimate frequency precision that can be reached. In quantum metrology, where the phase of a qubit is used to detect external fields, the clock stability is defined by the qubit coherence time, and therefore determines the spectral linewidth and frequency precision. I will present a demonstration of a quantum sensing protocol for oscillating fields where the spectral precision goes beyond the sensor coherence time and is limited by the stability of a classical clock. Using this technique, we observe a precision in frequency estimation scaling as $1/T^{3/2}$ for classical fields. The narrow linewidth magnetometer based on single quantum coherent spins in diamond is used to sense magnetic fields with an intrinsic frequency resolution of 607 Hz, 8 orders of magnitude narrower than the qubit coherence time.

NEWS ABOUT SHORTCUTS TO ADIABATICITY: SPATIAL NON-ADIABATIC PASSAGE

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Quantum technologies based on adiabatic techniques can be highly effective, but often at the cost of being very slow. In the first part, we will introduce a set of shortcut protocols for spatial state preparation, which yield the same fidelity as their adiabatic counterparts, but on fast timescales [1]. In particular, we consider a charged particle in a system of three tunnel-coupled quantum wells, where the presence of a magnetic field can induce a geometric phase during the tunnelling processes. We show that this leads to the appearance of complex tunnelling amplitudes and allows for the implementation of spatial non-adiabatic passage. We demonstrate the ability of such a system to transport a particle between two different wells and to generate a delocalised superposition between the three traps with high fidelity in short times.

In the second part, we switch back to adiabatic processes and we present a detailed derivation of the effect of Poisson Noise on adiabatic quantum control [2]. We discuss the limiting cases of Poisson white noise and provide approximations for the different noise strength regimes. We show that using the eigenstates of the noise superoperator as a basis can be a useful way of expressing the master equation. Using this, we simulate various settings to illustrate different effects of Poisson noise. In particular, we show a dip in the fidelity as a function of noise strength where high fidelity can occur in the strong-noise regime for some cases.

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GENERATION OF NON-ABELIAN GEOMETRIC PHASES IN DEGENERATE ATOMIC TRANSITIONS

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A popular quantum system, in which the Pancharatnam-Berry non-Abelian geometric phase has been generated and exploited, is the atomic tripod system. It is conveniently created by linking a single atomic state with three other states by three electromagnetic fields. Such a linkage pattern naturally emerges between the magnetic sublevels of two atomic levels with angular momenta $J = 0$ and $J = 1$, although tripod implementations between other suitable sublevels are also used. Here we go beyond the limitation of a tripod system and show that it is possible to generate the non- Abelian geometric phase in a quantum system composed of N lower and $N-2$ upper sublevels. The theoretical instrument is the Morris-Shore transformation which reveals the existence of two uncoupled (dark) states composed of the lower sublevels only. A possible physical implementation is the atomic transition J to $J-1$, with J arbitrary, which is driven, as in the case of tripod system, by three electromagnetic fields of different polarizations. This generalization considerably broadens the range of systems that can be used to generate a geometric phase, with the the same experimental complexity as in the tripod system. Specific calculations of the non-Abelian geometric phase are presented for $J = 3/2$ to $J = 1/2$ and $J = 2$ to $J = 1$ systems. A method for measuring the geometric phase is proposed.

DISPERSION-ENHANCED THIRD-HARMONIC MICROSCOPY

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In the past two decades coherent nonlinear microscopy (CNM) developed into a powerful and broadly applied tool for three-dimensional imaging of transparent sample. CNM utilizes frequency conversion processes in strongly focused, ultrashort laser pulses. It even delivers images of otherwise fully transparent samples, which are not accessible by conventional linear microscopy without marking or staining. One example for CNM processes is third harmonic generation (THG). In the case of tight focussing, the Gouy phase shift in the focus causes destructive interference for third harmonic generation in a bulk sample. Thus, net THG emission occurs only at interfaces. Three-dimensional imaging is possible by scanning the laser focus across the sample. This permits high contrast 3D imaging of boundaries in heterogeneous samples. In this talk we demonstrate strong enhancements of signal yield and image contrast in third-harmonic microscopy by appropriate choice of driving laser wavelength to modulate the phase-matching conditions of the conversion process by dispersion control [1]. Tuning the laser wavelength in the range of 1010-1350 nm at samples containing interfaces with water and glass, we obtained large signal enhancements up to a factor of 19, and improvements in the image contrast by an order of magnitude. A simple theoretical calculation, using a constant ratio of susceptibilities in the media, matches very well with the experimental data.

[1] C. Stock, K. Zlatanov, T. Halfmann, Opt. Commun. **393**, 289293 (2017).

COHERENT POPULATION OSCILLATIONS IN NV COLOUR CENTRES IN DIAMOND

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Nitrogen-vacancy (NV-) colour centres are point defects in the diamond lattice, consisting of a substitutional nitrogen atom adjacent to a lattice vacancy. A nonzero electron spin ($S = 1$) of those centres allows them to be optically pumped, and then probed via microwave spectroscopy. This property makes them useful in numerous applications including electric-field, magnetic-field, pressure, and temperature sensing, as well as nanoscale NMR. Nanodiamonds can also be used as fluorescent markers or sensors in biological materials. We present the results of our research on microwave spectroscopy in nitrogen-vacancy colour centres in a diamond. In particular, we focus on the case of two microwave fields and apply the optically-detected magnetic resonance technique to study the microwave hole burning. When both microwaves are tuned to transitions between ms $= 0 \leftrightarrow$ ms $= +1$ spin sublevels of the NV-ensemble in the 3A2 ground state, the observed spectra exhibit a complex narrow structure composed of three Lorentzian resonances positioned at the pump-field frequency. The resonance widths and amplitudes depend on the lifetimes of the levels involved in the transition. We attribute the spectra to coherent population oscillations induced by the two nearly degenerate microwave fields, which we have also observed in real time. The observations agree well with a theoretical model and can be useful for investigation of the NV- relaxation mechanisms.

PSEUDO-HERMITIAN LANDAU-ZENER MODEL

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We derive the analytical solution of the model of a two-state system interacting with an external coherent field, in which the Hamiltonian is pseudo-Hermitian. We describe in detail the non-Hermitian generalization of the famed Landau-Zener-Stückelberg-Majorana model, but similar generalizations can be derived in a very simple fashion for the other analytically soluble two-state models. The analytical solutions possess a non-Hermitian dynamical invariant, which replaces the probability conservation condition in the Hermitian case. Implementations in waveguide optics and nonlinear frequency conversion are suggested.

TOWARDS A HIGH RESOLUTION RB$^+$ FIB

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The atomic beam laser-cooled ion source (ABLIS) project [1] is aimed at creating an ultracold rubidium ion beam by the photo-ionisation of a laser-cooled and compressed thermal atomic beam. This ion beam will be used in a new focused ion beam (FIB) apparatus. Such systems are widely used in science and industry for sample inspection and manipulation at the nano-scale. Current gallium liquid metal ion source (LMIS) based FIBs can image and alter structures with a resolution down to 5 nm at a beam current of 1 pA and a beam energy of 30 keV. However, with the decrease in feature size achievable with photo-lithographic techniques, the FIB spot size needs to shrink as well in order to keep circuit edit and repair viable. A smaller spot size in a FIB can be realised by increasing the ion beam brightness and/or by decreasing its longitudinal energy spread. The ABLIS project aims at creating an ion source that achieves both. In short, laser cooling and compression is applied to a thermal atomic beam of rubidium atoms to achieve the desired brightness. Then, two-step photo-ionisation in an electric field is applied to turn all atoms into ions while minimising heating due to Coulomb effects, thus preserving the brightness [2]. Keeping the ionisation volume small ensures that the longitudinal energy spread is minimised. Note that other research groups are working on ion sources based on similar ideas [3]. In this contribution an overview is given of the experimental realisation of the atomic beam laser-cooled ion source [4]. A high degree of ionisation is achieved in order to generate an ion beam with similar brightness as the atomic beam. Furthermore, to minimise the longitudinal energy spread that is introduced due to the accelerating electric field, ionisation should take place in an as small as possible length. Experiments were carried out to find the highest ionisation degree and to verify the modelling. Apart from the beam brightness, the longitudinal energy spread of the ion beam plays an important role in the formation of a small spot due to chromatic abberations in the electrostatic lens column. Here, a retarding field analyser was used to measure the energy spread. Currently, steps are taken to mount the ion source on a commercial FIB system.

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[4] G. ten Haaf et al., Phys. Rev. Appl. **7**, 054013 (2017).

QUANTUM ENGINEERING: ON QKD AND UV LASING WITHOUT INVERSION

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In this talk we present the current status of two of our experiments. First, we present recent progress on the characterisation of our single photon sources based on spontaneous parametric down conversion in quantum key distribution. In particular, we discuss the spectral properties of the generated photons.

During the second part of the talk we will detail the advances of our efforts building a UV laser based on lasing without inversion. After a recent theoretical study has shown the principle feasibility of our approach employing a four level double dark scheme in mercury [1], our first measurements regarding amplification without inversion (AWI) lead to the observation of Doppler-free three-photon coherences. While our pump was not strong enough to show AWI, the theoretical model is in good agreement with our results and a prediction for the necessary pump power was determined [2].

[1] M. R. Sturm, B. Rein, Th. Walther and R. Walser, J. Opt. Soc. Am. B **31** 1964, (2014);
[2] B. Rein, J. Schmitt, M. Sturm, R. Walser, T. Walther, to be published (2017).

BICHROMATIC CONTROL OF MULTI-PHOTON IONIZATION

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Polarization-tailored bichromatic laser fields have emerged as new twist to steer ultrafast electron dynamics on their intrinsic timescales. Recently, we introduced a novel approach to the generation of polarization-tailored bichromatic fields, based on ultrafast pulse shaping applied to an octave-spanning CEP-stable white light supercontinuum (WLS) [1-3]. The setup provides full control over all bichromatic pulse parameters such as the frequency and amplitude ratio, the spectral phase profile (including CEP and relative phase) and the polarization state of both colors. Bichromatic pulse shaping opens up a new class of polarization-tailored waveforms with application to multi-path coherent control of ultrafast dynamics, generation and control of high harmonics and the design of polarization-sensitive two-color pump-probe experiments with phase-locked CEP-stable laser pulses at a broad range of excitation wavelengths. In our experiments we employ polarization-shaped bichromatic fields to study resonance-enhanced multi-photon ionization (REMPI) of atoms as a prototype scenario for multi-path coherent control. Three-dimensional detection of the photoelectron momentum distribution by photoelectron imaging tomography provides detailed insights into the excitation and ionization dynamics. In addition, the generation of vortex-shaped photoelectron wave packets from single color REMPI of potassium atoms with sequences of two time-delayed CRCP few-cycle pulses is demonstrated [3].

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[2] S. Kerbstadt, L. Englert, T. Bayer, M. Wollenhaupt, Optics Express, (in print) (2017);

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ADIABATIC GENERATION OF ARBITRARY COHERENT SUPERPOSITIONS OF TWO QUANTUM STATES

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States of coherent superposition play a significant role in quantum optics and related fields. Applications are known in high precision measurements, atomic clocks, quantum information. Simple techniques for generating equal superposition states like a resonant $\pi/2$ pulse do not always work since they suffer efficiency limitations due to fluctuations of the control parameters and the environment. Among the various more sophisticated techniques are DEQSIE [1], shortcuts to adiabaticity and composite pulses for generating such states. Adiabatic techniques on the other hand have been harnessed for achieving robust population transfer and specific superposition states. We propose here a two-level adiabatic excitation scheme for generation of arbitrary superposition states via specific overlap of the Rabi frequency and the detuning's temporal profile. We use three known analytical models to demonstrate our approach: two trigonometric models and limiting cases of the hyperbolic Demkov-Kunike model.

[1] N. V. Vitanov and B. W. Shore, J. Phys. B: At. Mol. Opt. Phys. **48**, 174008 (2015).

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CAMEL XIII Programme

Time	Mon, June 19	Tue, June 20	Wed, June 21	Thu, June 22	Fri, June 23
09:00-09:40	Hensinger	Bruner	Walther	Pillet	round-table discussions (09:00-12:00)
09:40-10:20	Ospelkaus	Wollenhaupt	Kuhn	Hennrich	
10:20-11:00	coffee	coffee	coffee	coffee	
11:00-11:40	Garraway	Ahufinger	Banaczek	Keller	
11:40-12:20	Ruschhaupt	Busch	Piilo	Retzker	
12:20-12:40	Dowdall		Lyyra	Stock	
		trip (13:30-18:30)			
16:30	coffee		coffee	coffee	
17:00-17:40	Vredenbregt		Heinze	Militello	
17:40-18:10	Sycz		Genov	Simeonov	
18:10-18:40	Cournol		Torosov	Grimaudo	
18:40-19:00	Dorier		Laforgue	Zlatanov	

The workshop opens with a welcome drink on Sunday, June 18, at 20:00 in front of the lecture hall.

The boat trip will take place on Tuesday, June 20, starting at 14:00.

The conference dinner will take place on Wednesday, June 21, starting at 20:30.