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

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CAMEL VI

Sixth International Workshop

BOOK OF ABSTRACTS

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Svetoslav Ivanov and Nikolay Vitanov

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Quantum Optics and Quantum Information Group
Theoretical Physics Division
Department of Physics
Sofia University "St. Kliment Ohridski"
5 James Bourchier Blvd, 1164 Sofia, Bulgaria
http://camel6.quantum-bg.org/

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10:10-10:40 **Matthew Himsworth**, *Atom-photon interfaces for quantum networking*

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18:00-18:20 **Constantinos Lazarou**, *Dephasing effects on STIRAP in tripod configurations*

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10:10-10:40 **Vasiliy Entin**, *Control of the sign of subnatural resonances in counterpropagating laser beams*

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11:50-12:20 **Ioannis Thanopoulos**, *Intramolecular energy transfer in pyrazine by partitioning technique: A time-dependent perspective*

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17:40-18:00 **Ludmila Praxmeyer**, *Hybrid quantum repeaters*

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List of Abstracts

PHOTONS WALKING THE LINE

A. Schreiber, K. N. Cassemiro, V. Potocek, A. Gabris, P. Mosley, E. Andersson, I. Jex and C. Silberhorn

EPS/Physics, Heriot-Watt University, Edinburgh EH14 4AS, United Kingdom

email: E.Andersson@hw.ac.uk

The classical random walk is a fundamental model, describing phenomena ranging from material transport in media to the evolution of stock market shares. For a quantum walk, a superposition of different paths or positions leads to quantum interference. Quantum walks have been shown to speed up search problems and to play a role as a computational primitive. We show how to explore the physics of quantum walks using a robust, flexible and simple optical implementation. A straightforward setup would use a cascade of beam-splitters. Unfortunately such a complex network suffers from mechanical instabilities and requires a large number of optical components to realize more steps of the walk. We avoid this with a realization using optical fibres, employing a compact network loop. The same paths are re-used again and again, and the walk takes place in the time domain. Since one can easily operate with different coins, and since one may individually address time pulses by using commercially available fast electro-optical modulators (EOM), our work opens exciting new possibilities for the realization of quantum information protocols.

COLD MOLECULE FORMATION USING THE DEMKOV-KUNIKE FIELD CONFIGURATION

H. Azizbekyan

Kanaker Shrdjantseek toonel 110, 0052 Yerevan, Armenia

email: hrayrazizbekyan@gmail.com

Cold molecule formation via coherent photo- or magneto-association of ultracold atoms is discussed within the Demkov-Kunike model. The model is realized as a bell-shaped pulse and resonance-crossing detuning of finite variation. A recently proposed two-term ansatz that describes the relevant quadratic-nonlinear version of the level-crossing problem is analyzed. Three distinct interaction regimes (weak, intermediate and strong coupling limits) are revealed in the case of the large detuning variation range with a large resonance sweep rate. It is shown that the ansatz accurately describes the whole temporal dynamics of the association process in all the mentioned interaction regimes. A nonlinear saturation in this regime of interaction is found. Regardless of pulse area, this saturation limits the atom to molecule conversion probability that the system can reach. Comparison is made with the Landau-Zener model where the full conversion of atoms into molecules is theoretically possible.

TRANSITION TIME IN STIMULATED RAMAN ADIABATIC PASSAGE

I. I. Boradjiev and N. V. Vitanov

Department of Physics, Sofia University, 5 James Bourchier Blvd, 1164 Sofia, Bulgaria

email: boradjiev@phys.uni-sofia.bg

The technique of stimulated Raman adiabatic passage (STIRAP) is an efficient and robust technique for population transfer in three-state chainwise connected quantum systems, 1-2-3. In this work we analyze the transition time in STIRAP, that is the time it takes for the population to be transferred from state 1 to state 3. We derive a very simple formula for this transition time, which shows that it is inversely proportional to the nonadiabatic coupling, $\dot{\theta}(t_0)$, estimated at the time t_0 when the pump and Stokes couplings have the same value. Explicit formulas for several pairs of pump and Stokes pulses are derived. Contrary to the naive expectation that the transition time might be proportional to the delay between the pump and Stokes pulses, or to the width of their overlap region, we find that the transition time is inversely proportional to the delay, i.e. larger delays produce faster transitions.

GENERATION OF ULTRAFAST VISIBLE AND MID-IR PULSES VIA ADIABATIC FREQUENCY CONVERSION

B. Bruner

Department of Physics of Complex Systems, Rm. 306 Weizmann Institute of Science, Rehovot 76100, Israel

email: barry.bruner@weizmann.ac.il

A new method for efficient, broadband sum and difference frequency generation of ultrafast pulses is demonstrated. We demonstrate an analogy between frequency conversion and coherent optical excitation of a two-level system. This allows for the adaptation of well-known rapid adiabatic passage techniques to the context of frequency conversion. The scheme was implemented using aperiodically poled nonlinear crystals and a single step nonlinear mixing process. To date, broadband ultrafast conversion efficiencies up to 50% have been generated.

NOISE AND ENTANGLEMENT: FROM NATURAL PHOTOSYNTHESIS TO QUANTUM COMMUNICATION

F. Caruso

Ulm University, Institute of Theoretical Physics, Albert-Einstein-Allee 11, D - 89069 Ulm, Germany

email: filippo.caruso@uni-ulm.de

Recently, we investigated the intricate interplay of noise and quantum coherence to explain the remarkable efficiency well above 90% for excitation energy transfer (EET) in light harvesting complexes during photosynthesis. Here, we study the role of entanglement in these biological networks, even in the case of spatially and temporally correlated noise and for different injection mechanisms, like thermal and coherent laser excitation. While quantum information processing tends to favour maximal entanglement, the optimal EET efficiency is achieved when the initial part of the evolution displays intermediate values of entanglement. Finally, we investigate this transport dynamics in the elegant and powerful framework of quantum communication, and we find that the dephasing may enhance, in a very remarkable way, the capability of transmitting not only classical but also, more counterintuitively, quantum information over biologically inspired quantum communication networks.

ROBUST QUANTUM DOT STATE PREPARATION VIA ADIABATIC PASSAGE WITH CHIRPED PULSES

B. Chatel

CNRS-Université de Toulouse, UPS, Laboratoire Collisions, Agrégats Réactivité, IRSAMC, F-31062 Toulouse, France

email: beatrice@irsamc.ups-tlse.fr

The energy states in semiconductor quantum dots are discrete as in atoms, and quantum states can be coherently controlled with resonant laser pulses. Here, we report on the robust preparation of a quantum state using rapid adiabatic passage from the ground to an excited state through excitation with laser pulses whose frequency is swept in time through the resonance. This observation in photoluminescence experiments is made possible by introducing a novel detection scheme for the resonant electron hole pair (exciton) generation. This is the first experimental demonstration of rapid adiabatic passage in single quantum dot and opens the route towards coherent control scheme in such system.

IS THE ADIABATIC THEOREM VALID?

D. Comparat

Laboratoire Aimé Cotton, CNRS, Université Paris-Sud, Bâtiment 505, 91405 Orsay, France

email: daniel.comparat@u-psud.fre

Adiabaticity occurs when, during its evolution, a physical system remains in the instantaneous eigenstate of the hamiltonian. Following Landau-Zener or STIRAP processes, It is widely believed that the condition of a slow hamiltonian variation rate, compared to the spectral gap, is sufficient to ensure adiabaticity. We shall discuss this theorem and show that the theorem is true but only when the hamiltonian is real and non oscillating (for instance containing exponential or polynomial but no sinusoidal functions). Furthermore, we shall improve the quantum adiabatic theorem based on a slow down evolution ($H(\epsilon t)$, $\epsilon \to 0$), which is insufficient to describe an evolution driven by the hamiltonian $H(t)$ itself. Indeed, we shall derive general criteria and exact bounds, for the state and its phase, ensuring an adiabatic evolution for any hamiltonian $H(t)$.

CAVITY ELECTROMAGNETICALLY INDUCED TRANSPARENCY WITH ION COULOMB CRYSTALS

A. Dantan

QUANTOP, Department of Physics and Astronomy, University of Aarhus, Denmark

email: dantan@phys.au.dk

I will present recent CQED experiments with ion Coulomb crystals in optical cavities. By placing a moderately high-finesse cavity inside a linear ion trap and using large ensembles of ions, laser-cooled into a Coulomb crystal, it is possible to operate in the collective strong coupling regime of CQED at the single photon level. I will report on recent observations of cavity Electromagnetically Induced Transparency in such a system and discuss their applications for the realization of cavity EIT-based quantum memories as well as for the observation of photon blockade effects at the single photon level.

WAVELENGTH METER BASED ON COLOURED GLASS FILTER TRANSMISSION

G. Dobrev[1,2], I. Temelkov[1,2], A. Pashov[1]

Department of Physics, Sofia University, 5 James Bourchier Blvd, 1164 Sofia, Bulgaria

Institute of Solid State Physics, Bulgarian Academy of Sciences, 72 Tzarigradsko Shose Blvd, 1784 Sofia, Bulgaria

email: g_dobrev@phys.uni-sofia.bg

A simple wavemeter for measuring the wavelength of CW diode lasers is presented. The device is based on coloured glass filter transmission and its resolution is demonstrated to be better than 1Å. A group of factors, which have influence on accuracy and reproducibility of test results, are analysed. The presented results are from testing the wavemeter with CW diode laser and Ti:Al_2O_3 laser. Some useful applications of the device will be shown.

ULTRAFAST STIMULATED RAMAN PARALLEL ADIABATIC PASSAGE BY SHAPED PULSES

G. Dridi

Institut Carnot de Bourgogne, UMR 5209 CNRS, Université de Bourgogne, BP 47870, 21078 Dijon, France

email: ghassen.dridi@u-bourgogne.fr

We present a general and versatile technique of population transfer based on parallel adiabatic passage by femtosecond shaped pulses. Their amplitude and phase are specifically designed to optimize the adiabatic passage corresponding to parallel eigenvalues at all times. We show that this technique allows the robust adiabatic population transfer in a Raman system with the total pulses area as low as 3π, corresponding to a fluence of one order of magnitude below the conventional stimulated Raman adiabatic passage process. This process of short duration, typically picosecond and subpicosecond, is easily implementable with the modern pulse shaper technology and opens the possibility of ultrafast robust population transfer with interesting applications in quantum information processing.

CONTROL OF THE SIGN OF SUBNATURAL RESONANCES IN COUNTERPROPAGATING LASER BEAMS

V. M. Entin[1], D. V. Brazhnikov[2,3], A. V. Taichenachev[2,3], V. I. Yudin[2,3], I. I. Ryabtsev[1]

[1]Institute of Semiconductor Physics SB RAS, Pr. Acad. Lavrenteva 13, Novosibirsk, Russia

[2]Novosibirsk State University, ul. Pirogova 2 Novosibirsk, Russia

[3]Institute of Laser Physics Novosibirsk, Russia

email: ventin@isp.nsc.ru

The resonances of electromagnetically-induced transparency (EIT, [1]) and absorption (EIA, [2]) are the bright examples of nonlinear effects based on atomic coherences. Such EIT and EIA "subnatural" resonances have found various applications in nonlinear optics and optical communications ("slow" and "fast" light, four-wave mixing etc.) and metrology (atomic clocks and magnetometers). At the first time EIT as well as EIA were studied in the bichromatic unidirectional laser waves. However, from experimental viewpoint to observe these resonances an easier way may be exploited using so-called Hanle configuration [3]. It requires only one traveling light wave and the spectroscopic signal is absorption versus static magnetic field applied along the vapour cell. At that the subnatural resonance is connected with a crossing of magnetic sublevels in ground state (level-crossing resonance). Besides studying the parameters of subnatural resonances (width, amplitude, contrast, shift), the problem of its sign has a special interest. It is known that a sign of the subnatural resonance depends on such factors as structure of energy levels [2,4], collisions of atoms with buffer gas or walls of cell [5], microwave [6] or static magnetic fields [7] and some others. In this paper we propose new easy and effective method [8] for controlling of the sign of subnatural resonance in Hanle configuration. We have discussed the scheme being composed of two counterpropagating overlapped light waves with same frequency and static magnetic field applied along the cell. The sign of the resonance can be governed by varying either the angle between the polarizations or the ellipticities. Numerical calculations show that the sign-reversal effect exists for dark-type atomic transitions (e.g. $F = 2$ to $F = 1$) as well as for bright ones (in particular, $F = 2$ to $F = 3$). Explicit analytical results and clear physical interpretation are gained using Lambda-atom model. Main theoretical conclusions have been proved by our experiments made at the $F = 2$ to $F = 1$ transition of D1-line in 87Rb. It should be noted that the method proposed, in principle, may provide high-contrast EIA resonances even in presence of buffer gas, when collisional depolarization of exited state occurs.

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DECAY ANALYSIS WITH RESERVOIR STRUCTURES

B. Garraway

Department of Physics and Astronomy, University of Sussex, Falmer, Brighton, BN1 9QH, United Kingdom

email: b.m.garraway@sussex.ac.uk

Static reservoir structures coupled to simple quantum systems can be analysed by the method of "pseudomodes" [1], where the reservoir structure is replaced by an effective mode. The approach can be useful for strongly coupled, i.e. non-Markovian problems. An introduction to this theory will be given with some simple examples and recent results involving reservoir memory [2] and entanglement in the reservoir [3].

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ENTANGLEMENT LOCALIZATION ON A THREE-PHOTON SYSTEM

M. Gavenda

Deptartment of Optics, Faculty of Science, Palacky University Olomouc, 17. listopadu 12, 77146 Olomouc, Czech Republic

email: gavenda@optics.upol.cz

We discuss both theoretically and experimentally an elementary two-photon polarization entanglement localization after break of entanglement caused by linear coupling of environmental photon with one of the system photons [1]. The localization of entanglement is based on simple polarization measurement of the surrounding photon after the coupling. We demonstrate that non-zero entanglement can be localized back irrespectively to the distinguishability of coupled photons. Further, it can be increased by local single-copy polarization filters up to an amount violating Bell inequalities [2]. The present technique allows to restore entanglement in that cases, when the entanglement distillation does not produce any entanglement out of the coupling.

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COMPOSITE PULSES FOR THREE-STATE QUANTUM SYSTEMS

G. T. Genov, B. T. Torosov, N. V. Vitanov

Department of Physics, Sofia University, 5 James Bourchier Blvd, 1164 Sofia, Bulgaria

email: genko.genov@quantum-bg.org

Composite pulses are used in nuclear magnetic resonance [1,2], and most recently, in trapped-ion quantum information processing [3], for design of qubit rotations that are more robust against variations in the pulse area and/or the detuning than single resonant pulses of precise area. The composite pulse is a sequence of pulses with well defined relative phases between each other. The composite pulses can be considered as an alternative method to adiabatic pulses with similar robustness and higher fidelity.

In this work we describe the design of composite pulses for three-state chain-wise connected quantum systems. These pulses can be used in three different situations depicted. For equal couplings and equidistant detunings, we use the Majorana decomposition [4,5] to reduce the dynamics to an effective two-state system, which allows us to find the three-state propagator analytically and use the pool of available composite pulses. For different couplings and two-photon resonance, we use the Morris-Shore decomposition [6], which again reduces the dynamics to an effective two-state problem and allows us to find the propagator analytically. Finally, in the general case of different couplings and different detunings, we resort to numerical simulation [7].

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ON THE SPECTRAL PROPERTIES OF LAX OPERATORS

V. Gerdjikov

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 72 Tsarigradsko chaussee, 1784 Sofia, Bulgaria

email: gerjikov@inrne.bas.bg

I will consider a class of Lax operators generalizing the Zakharov-Shabat system:

$$L\psi \equiv i\frac{d\psi}{dx} + (Q(x) - \lambda J)\psi(x,\lambda) = 0, \qquad (1)$$

where $Q(x)$ and J take values in a simple Lie algebra $\mathfrak{g}$ and vanishes fast enough for $x \to \pm\infty$. Applying the inverse scattering method to L one is able to solve a number of important nonlinear evolution equations (NLEE) such as multicomponent nonlinear Schrodinger equations, N-wave equations, etc.

We will construct the fundamental analytic solutions of L and will show the important they play in constructing the spectral decompositions of L. The FAS satisfy a Riemann-Hilbert problem, which allows one to use the dressing Zakharov-Shabat method for constructing the reflectionless potentials of L and the soliton solutions of the NLEE.

Another important field of applications of these results is in the quantum mechanics of multi-level atomic systems.

DETERMINISTIC GENERATION OF INDISTINGUISHABLE SINGLE-PHOTON PULSES

A. Gogyan

Institut Carnot de Bourgogne, Universite de Bourgogne, 9, Av A. Savary, 21078 Dijon, France

email: agogyan@gmail.com

The success of many tasks in optical quantum information processing crucially depends on the generation of high-quality single-photon (SP) states. To make a good SP source one has to ensure suppression of both the multi-photon and the zero-photon state, as well as to eliminate the entanglement between the photons which degrades the purity of the SP state. We propose a mechanism to produce indistinguishable single-photon pulses on demand from an optical cavity. The sequences of two laser pulses generate, at the two Raman transitions of a four-level atom, the same cavity-mode photons without repumping of the atom between photon generations. Photons are emitted from the cavity with near-unit efficiency in well-defined temporal modes of identical shapes controlled by the laser fields. The second order correlation function reveals the single-photon nature of the proposed source. A realistic setup for the experimental implementation is presented.

CONTROL BY FAST PARALLEL ADIABATIC PASSAGE. APPLICATION FOR QUANTUM MACHINES

S. Guérin

Institut Carnot de Bourgogne, Universite de Bourgogne, 9, Av A. Savary, 21078 Dijon, France

email: sguerin@u-bourgogne.fr

We present the technique of fast parallel adiabatic passage and its application to the control of quantum processes such as state-selectivity, quantum information processing, and to the manipulation of the rotation of molecules to implement quantum machines. This technique corresponds to an adiabatic passage for which the instantaneous eigenvalues are parallel at each time. It induces a very efficient population transfer in terms of pulse energy and duration, while preserving the standard robustness of adiabatic techniques. It can be implemented with the modern technology of liquid crystal spatial light modulators. This opens the possibility to implement a STIRAP-like technique in a sub-picosecond regime. It can be applied to the control of the alignment and the rotation of molecules in order to produce quantum machines such as a quantum gear.

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MULTIPHOTON PARALLEL ADIABATIC PASSAGE BY SHAPED PULSES

V. Hakobyan

Institut Carnot de Bourgogne, Universite de Bourgogne, 9, Av A. Savary, 21078 Dijon, France

email: vahe.hakobyan@u-bourgogne.fr

The strategy to optimally populate the excited state from the initial ground state by adiabatic passage is to follow a level line in the diagram of the difference of the instantaneous eigenenergies. This corresponds to a dynamics featuring parallel instantaneous eigenenergies at all times. This strategy is referred to as an optimal adiabatic passage as it allows the nonadiabatic correction to be suppressed in the adiabatic limit, as shown with the Davis-Dykhne-Pechukas formalism. We study a multiphoton process between an initially populated ground state and an excited states for the atom of Cs driven by a two-photon process such that the Stark shift can be fully compensated to recover the efficiency of the population transfer by a one-photon resonant process. This can be produced using the technique of pulse shaping in the frequency domain.

COHERENT OPTICAL DATA STORAGE AND PROCESSING IN A DOPED SOLID

T. Halfmann

Institute of Applied Physics, Technical University of Darmstadt, 64289 Darmstadt, Germany

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

Coherent interactions between light and matter provide powerful tools to control optical properties and processes in any type of quantized medium. Among others, contemporary research efforts aim at efficient storage and processing of optically encoded data, e.g. as required in quantum information processing. The talk presents experimental implementations of coherent laser-driven interactions in particular solid media, i.e. rare-earth doped solids. The latter media combine the advantages of atoms in the gas phase (i.e. spectrally narrow transitions) with the advantages of solids (i.e. large density and scalability). The talk reports on experimental implementations of electro-magnetically-induced transparency (EIT) and dark-state polaritons (DSPs), different versions of stimulated Raman adiabatic passage (STIRAP), dynamic decoherence control, and feedback-controlled pulse shaping in a rare-earth doped solid, to store and process optically-encoded information in a doped solid.

SCALABLE QUANTUM TECHNOLOGY WITH TRAPPED YTTERBIUM IONS

W. Hensinger

Ion Quantum Technology Group, Department of Physics and Astronomy, University of Sussex, Falmer, Brighton, East Sussex, BN1 9QH, United Kingdom

email: w.k.hensinger@suss ex.ac.uk

We have trapped single ytterbium ions in an experimental setup particularly designed for the development of advanced ion trap chips. This setup allows for rapid turn-around time, optical access for all type of ion trap chips and up to 100 electric interconnects. The particular ion trap used features an ion – electrode distance of 310 microns and secular frequencies on the order of 1 MHz and we have observed ion life times in excess of 15 hours. We measured the motional heating rate and obtained a value for the electric field noise of $S(1\text{MHz}) = 3.6 \times 10^{11}(\text{V/m})^2\text{Hz}^{-1}$. We also accomplished isotope selective loading. Incorporating MEMS fabrication technologies we report on design and fabrication of a multi-zone y-junction surface-electrode ion trap in which all dielectrics are optically and electrically shielded. We also present progress on a microfabricated 2-D ion trap array that allows for the creation of ion lattices for the implementation of a quantum simulator. The separation of ions within an ion trap array is important and we present optimal electrode configurations in surface ion traps. We also report on our studies for the development of optimal junctions.

ATOM-PHOTON INTERFACES FOR QUANTUM NETWORKING

M. Himsworth

Atomic and Laser Physics, Clarendon Laboratory, University of Oxford, OX1 3PU Oxford, United Kingdom

email: m.himsworth1@physics.ox.ac.uk

Atoms coupled to high finesse cavities are seen as a promising candidate for quantum network nodes. A stream of identical photons can be emitted from the cavity, using vacuum-STIRAP, with a high probability which are necessary for several quantum networking protocols. The photons can be controlled in both polarization and spatio-temporal profile and may be entangled with the cavity-atom or in photon pairs. An efficient scalable quantum network would require additional elements such as memory and routing, and these may be realized with light storage via electromagnetically induced transparency and controllable dipole traps, respectively. This talk with cover the theoretical and experimental progress in addressing each of the above elements at the University of Oxford.

DYNAMICAL CONTROL AND NOVEL QUANTUM PHASES IN IMPURITY DOPED LINEAR ION CRYSTALS

P. A. Ivanov[1], N. V. Vitanov[2], K. Singer[1], and F. Schmidt-Kaler[1]

[1]Institut für Physik, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany

[2]Department of Physics, Sofia University, 5 James Bourchier Blvd, 1164 Sofia, Bulgaria

email: pivanov@phys.uni-sofia.bg

We consider the behavior of the phonon number distribution in an heterogeneous linear ion crystal doped with single impurity ion. The presence of ion species with different masses changes dramatically the transverse energy spectrum, in such a way that two eigenfrequencies become non-analytic functions of the mass ratio in the form of a sharp cusp. This non-analyticity induces a quantum phase transition between condensed and conducting phase of the transverse local phonons. In order to continuously vary the mass ratio we propose to use a locally applied laser field, exerting optical dipole forces which reduces the effective mass.

1. Peter A. Ivanov, Nikolay V. Vitanov, Kilian Singer, and Ferdinand Schmidt-Kaler, arXiv:1002.3033.

SCALABLE QUANTUM SEARCH USING TRAPPED IONS

S. S. Ivanov[1,2], P. A. Ivanov[1,3], I. E. Linington[1], and N. V. Vitanov[1]

[1]Department of Physics, Sofia University, 5 James Bourchier Blvd, 1164 Sofia, Bulgaria

[2]ICB, Université de Bourgogne, UMR CNRS 5209, Dijon, France

[3]Institut für Quanteninformationsverarbeitung, Universität Ulm, Albert-Einstein-Allee 11, D-89081 Ulm, Germany

email: svetivanov@phys.uni-sofia.bg

We propose a scalable implementation of Grover's quantum search algorithm in a trapped-ion quantum information processor. The system is initialized in an entangled Dicke state by using adiabatic techniques. The inversion-about-average and the oracle operators take the form of *single* off-resonant laser pulses. This is made possible by utilizing the physical symmetries of the trapped-ion linear crystal. The physical realization of the algorithm represents a dramatic simplification: each logical iteration (oracle and inversion about average) requires only *two* physical interaction steps, in contrast to the large number of concatenated gates required by previous approaches.

MEASURE FOR THE NON-MARKOVIANITY OF QUANTUM PROCESSES

E.-M. Laine

Kaivokatu 16 bA 4, 20520 Turku, Finland

email: emelai@utu.fi

A Markov process in the evolution of an open quantum system gives rise to a quantum dynamical semigroup, for which the most general representation of the dynamics can be written in the Lindblad form. There exists complex systems for which the relatively simple description of the open system dynamics given by a Markovian master equation fails to give a comprehensive picture of the dynamics. Thus in many realistic physical systems the Markovian approximation of the dynamics gives an overly simplified picture of the open system evolution and a more rigorous description of the dynamics is required.

To give insight into the nature of non-Markovian effects many analytical methods and numerical simulation techniques have been developed in recent years. Non-Markovianity manifests itself in the different approaches in a variety of ways and there exists no recipe for comparing the degree of non-Markovianity between the different approaches. In order to give a general quantity determining the degree of non-Markovian behavior in the open system dynamics, one has to rigorously define what makes a dynamical map non- Markovian.

We introduce a general measure for the degree of non-Markovian behavior in an open quantum system by quantifying the information flow from the environment to the open system [1, 2]. The change in the distinguishability of states of the open system can be interpreted as information flow between the system and the environment. Thus the measure for non-Markovianity can be constructed from the concept of trace distance, which quantifies the distinguishability of quantum states. If the distinguishability is always decreasing, then the system is Markovian. Increase in the distinguishability at certain times indicates information flow from the environment to the system and therefore non-Markovian behavior.

This criterion for non-Markovianity does not require knowledge about the details of the environment or the system-environment interaction. Instead, tomographic measurements of a system can quantify the extent to which a system exhibits non-Markovian behavior.

1. H.-P. Breuer, E.-M. Laine, J. Piilo, Phys. Rev. Lett. **103**, 210401 (2009).
2. E.-M. Laine, J. Piilo, H.-P. Breuer, arXiv: 1002.2583 [quant-ph].

INTERFACING SINGLE IONS AND SINGLE PHOTONS

W. Lange

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

email: W.Lange@sussex.ac.uk

An interface between quantum states of ions and photons is a tool of central importance in quantum information processing, linking the two most important qubit carriers. To couple the quantum states of ions and photons reversibly and with high fidelity is a challenging task, requiring as a tight integration of miniature optical cavities and traps. We investigate three different routes to this end. For moderate coupling, we attempt to generate quantum entanglement probabilistically, projecting ions to an entangled state upon detecting photons emitted from the cavity. For stronger coupling, deterministic transfer of quantum states between ions and photons is possible. In order to maximize the coupling, we will employ ultra-small fibre cavities, closely fitted to the electrode structure of the ion trap. Entanglement of ions in a cavity may even be generated through the exchange of virtual photons. In this case, a miniature linear ion trap is used.

DEPHASING EFFECTS ON STIRAP IN TRIPOD CONFIGURATIONS

C. Lazarou

Department of Physics, Sofia University, 5 James Bourchier Blvd, 1164 Sofia, Bulgaria

email: constantinos.lazarou@quantum-bg.org

We develop an effective two-level model that describes dephasing effects in a tripod configuration. Our analysis makes use of the adiabatic approximation, in the weak dephasing regime. An effective master equation for a two-level system formed by two dark states is derived. Solutions are utilized in terms of two-level crossing models. The population and coherences exponentially decay with respect to the relaxation rates, whereas for adiabatic evolution the pulse delay has an inverse effect, depending on the pulse ordering. The fidelity of the final coherent state deteriorates for increasing decay rates, and increases when the pulse delay is increased.

LONG LIFE TO QUANTUM CORRELATIONS!

S. Maniscalco

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

email: smanis@utu.fi

We study the dynamics of quantum and classical correlations in the presence of decoherence. We discover a class of initial states for which the quantum correlations, quantified by the quantum discord, are not destroyed by decoherence for times $t < t^*$. In this initial time interval only classical correlations decay. For $t > t^*$, on the other hand, classical correlations do not change in time and only quantum correlations are lost due to the interaction with the environment. Therefore, at the transition time t^* the open system dynamics exhibits a sudden transition from classical to quantum decoherence regime.

FROZEN DISCORD AND DYNAMICS OF CORRELATIONS IN NON-MARKOVIAN CHANNELS

L. Mazzola

Linnankatu 37 b 35, 20100, Department of Physics and Astronomy, University of Turku, Finland

email: laumaz@utu.fi

In the last couple of years a big deal of attention has been devoted to the study of quantum and classical correlations in quantum mechanical systems. After the realization that there can be nonclassical correlations which are not necessarily captured by entanglement, we have witnessed a flourishing of works aiming at defining, quantifying and studying the dynamics of these properties in different kinds of systems. Recently we have discovered that there exist physical systems in which quantum correlations described by quantum discord can be unaffected by environmental noise for a long period of time. In particular in Ref. [1] we have shown that two qubits under local depolarizing channels can exhibit what we have called a transition between classical and quantum decoherence. Here we study the dynamics of quantum and classical correlations and spot the transition between quantum and classical decoherence for a more general type of noise. We use a well established model describing the dynamics of a two level system under depolarizing channel in which white noise is replaced by colored noise. The memory effects and the backflow of information from the environment to the system blur the simple picture of the white noise case. However it is still possible to distinguish different dynamical regimes for quantum and classical correlations. We also present a geometrical interpretation of invariant-under decoherence discord in terms of the distance to the closest classical state.

1. L. Mazzola, J. Piilo, and S. Maniscalco, arXiv:1001.5441v3, accepted by Phys. Rev. Lett.

COHERENT CONTROL OF FREQUENCY CONVERSION TOWARDS SHORT (PICOSECOND) VACUUM-ULTRAVIOLET RADIATION PULSES

H. Münch, S. Chakrabarti, T. Halfmann

Institute of Applied Physics, Technical University of Darmstadt, 64289 Darmstadt, Germany

email: holger.muench@physik.tu-darmstadt.de

We present experimental data on coherent control of frequency conversion towards the vacuum-ultraviolet (VUV) regime in xenon atoms, applying intense ultra-short picoseconds (ps) radiation pulses. The coupling scheme involves resonantly-enhanced fifth harmonic generation (FHG) via the 5p $^1S_0 8d^2[1/2]_1$ transition in xenon, driven by a short (ps) radiation pulse at 530 nm, yielding VUV radiation at 106 nm. A simultaneous resonantly-enhanced four-wave mixing (FWM) process, driven by the fundamental (ps) laser pulse at 530 nm and its phase-locked second harmonic at 265 nm, also yields radiation at 106 nm. The two frequency conversion pathways interfere with each other. The interference is either constructive or destructive, depending on the relative phase of the radiation pulses. We adjust the phase of the fundamental (ps) laser pulse, subsequent to the frequency doubling, by passing it through a closed cell filled with argon. Therefore, by variation of the argon pressure and thus the phase in the fundamental (ps) laser pulse, we observe pronounced enhancement and suppression of the conversion efficiency towards VUV radiation.

FROM ULTRACOLD TO ULTRAHOT: QUASI-RELATIVISTIC DYNAMICS FOR COLD ATOMS

P. Öhberg

SUPA, School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, United Kingdom

email: P.Ohberg@hw.ac.uk

In this talk we will show how a gas of ultracold atoms can be described by an effective Dirac equation. The underlying machinery for creating such a gas is based on optically induced gauge potentials and dark state dynamics. We will briefly outline the concept of artificial electromagnetism and illustrate this by looking at confinement mechanisms in the gas, a concept which is also known from quantum chromodynamics and high energy physics.

ADIABATIC MARKOVIAN DYNAMICS

O. Oreshkov

Quantum Optics, Quantum Nanophysics, Quantum Information, University of Vienna, Boltzmanngasse 5, Room 3315, 1090 Vienna

email: ooreshkov@gmail.com

We propose a theory of adiabaticity in quantum Markovian dynamics based on a structural decomposition of the Hilbert space induced by the asymptotic behavior of the Lindblad semigroup. A central idea of our approach is that the natural generalization of the concept of eigenspace of the Hamiltonian in the case of Markovian dynamics is a noiseless subsystem with a minimal noisy cofactor. Unlike previous attempts to define adiabaticity for open systems, our approach deals exclusively with physical entities and provides a simple, intuitive picture at the underlying Hilbert-space level, linking the notion of adiabaticity to the theory of noiseless subsystems. As an application of our theory, we propose a framework for decoherence-assisted computation in noiseless codes under general Markovian noise. We also formulate a dissipation-driven approach to holonomic computation based on adiabatic dragging of subsystems that is generally not achievable by non-dissipative means.

STUDIES OF COLD ATOMIC COLLISIONS BY MOLECULAR SPECTROSCOPY

A. Pashov

Department of Physics, Sofia University, 5 James Bourchier Blvd, 1164 Sofia, Bulgaria

email: pashov@phys.uni-sofia.bg

The progress in the laser cooling and trapping of atoms set new requirements for the molecular spectroscopy. Usually concentrated on the equilibrium distance properties of the system of two bound atoms, now the spectroscopists concentrated on the long-range properties of the molecular potentials. In this contribution the recent results of these spectroscopic studies will be presented with an accent set on the application of modeling interactions between two cold atoms and the formation of cold molecules.

ALL-OPTICAL CAVITIES FOR LIGHT: FROM STORED TO STATIONARY LIGHT

T. Peters

Institute of Applied Physics, Technical University of Darmstadt, 64289 Darmstadt, Germany

email: thorsten.peters@physik.tu-darmstadt.de

Creating light pulses with ultralow group velocities and "storage and retrieval" of light pulses based on electromagnetically induced transparency (EIT) have become standard techniques in recent years. As the interaction time of light pulses with a medium can be dramatically increased without inducing additional losses, future applications in the field of quantum information processing (QIP) are under development. However, non-linear optical interactions, which are required for QIP, are so far rather inefficient as their efficiency is proportional to the intensity and the interaction time of the light pulses. To overcome this problem, the formation of light pulses with stationary spatio-temporal envelopes has been proposed and demonstrated a few years ago in a medium comprised of hot atoms. Since then there had been a theoretical discussion whether or not stationary light pulses (SLPs) could also be formed in cold media. In this talk, I will discuss the underlying physics of SLP formation, their relation to slow and stored light and why the medium temperature plays an important role in their formation. Following this discussion I will present experimental results on the first successful creation of SLPs in a medium of laser-cooled atoms and how their formation can be actively controlled. All experimental data will be compared to results of numerical simulations.

HYBRID QUANTUM REPEATERS

L. Praxmeyer

Institute of Physics, Nicolaus Copernicus University, ul. Grudziadzka 5, 87-100 Torun, Poland

email: lpraxm@gmail.com

We shall analyze a performance of the hybrid quantum repeater scheme in an idealized case of perfect quantum memory as well as in a more realistic case of finite memory time. Formulas for the rates that can be obtained in this scheme were calculated analytically by probabilistic combinatorial methods. This analytical approach makes our results unique because typically such a rate analysis is done by purely numerical calculations.

VIBRATIONAL QUANTUM DEFECT TO ANALYZE WEAKLY-BOUND MOLECULE SPECTRA. APPLICATION TO CS_2 TO DETECT COUPLED STATES

L. Pruvost, H. Jelassi

[1]Laboratoire Aimé Cotton, CNRS, Université Paris-Sud, Bâtiment 505, 91405 Orsay, France

[2]Centre National des Sciences et Technologies Nucléaires 2020 Sidi Thabet, Tunisie

email: laurence.pruvost@lac.u-psud.fr

To form cold molecules starting from cold atoms, many processes have been demonstrated: for example photoassociation (PA) or magneto-association. In the case of the PA use, the scheme which ends to a molecule in the ground state is generally composed by many steps. The simplest scheme uses two steps: (1) the PA of a pair of cold atoms to an excited molecular level, and (2) a natural or induced decay of the excited molecule to a ground state. The processes (1) and (2) are optimized when the intermediate state (the excited molecule) has a wavefunction with two regions of large probability: one at long range distance which allows the PA process and another one at short range distance which enhances the decay into a vibrational ground state. Such wavefunctions occasionally exist when the intermediate state results of the coupling between two molecular curves, in the vicinity of quasi resonant levels. To detect such intermediate states, a careful analysis of the spectroscopic data is required. In this context, we have applied the method of the vibrational quantum defect [1] to analyse spectroscopic data of weakly-bound molecules. The method joins the LeRoy-Bernstein formula and the quantum defect theory. A plot of the quantum defect versus the energy allows to exhibit the coupled states, and its fit by a model of coupled series allows to determine the amplitude of the coupling, the location of the levels and the mixing of the wavefunctions. We illustrate the method with the analysis of Cs_2 data [2] of weakly bound levels of the $6s_{1/2} - 6p_{1/2} 0_u^+$ and 0_g^- series [3,4]. We show and characterize many coupling regions which are interested for cold molecule formation.

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COLD ATOM GUIDED IN A SLM-GENERATED LAGUERRE-GAUSSIAN LASER MODE

B. Viaris de Lesegno, F. Diry, M. Mestre, L. Pruvost

Laboratoire Aimé Cotton, CNRS, Université Paris-Sud, Bâtiment 505, 91405 Orsay, France

email: laurence.pruvost@lac.u-psud.fr

In the context of cold atom manipulation or trapping, optical potentials realized with a laser far-detuned from the atomic transition, constitute efficient tools to perform experiments without destroying the initial properties of the cold sample. For example, the use of very far detuned optical potentials avoids sample heating and preserves the coherence properties in the case of Bose-Einstein condensate use. The shape of the optical potential is determined by the intensity profile of the laser beam. Shaping the laser thus would allow to design optical potentials with particular geometries or with shapes. To shape the laser, we apply a holographic method in which the hologram is a phase-only spatial light modulator (SLM). We first used such a device to transform a TEM_{00} laser mode into a Laguerre-Gaussian (LG) mode. Then, we generated LG modes deformed into polygons or opened rings. The LG modes were applied to rubidium cold atoms to guide them in the dark center of the mode. We have performed a quantitative study [1] of the guiding efficiency versus the order of the LG mode and versus the laser detuning. We explained the increase of the efficiency versus the mode order using a two-dimensional trap model giving the capture efficiency. Other applications of LG modes and applications of deformed LG modes are conceivable. For example, crossed LG modes could provide 3-dimensional configurations allowing power-law potentials for Bose-Einstein condensation [2]. Opened, and deformed LG modes could design trap geometry for study atom dynamics -regular or chaotic.

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STIMULATED RAMAN ADIABATIC PASSAGE IN POLARIZATION PHYSICS; BROADBAND ADIABATIC CONVERSION OF LIGHT POLARIZATION

A. A. Rangelov[1], U. Gaubatz[2], N. V. Vitanov[1]

[1]Department of Physics, Sofia University, 5 James Bourchier Blvd, 1164 Sofia, Bulgaria

[2]Nokia Siemens Networks GmbH & Co. KG, St.-Martin-Strasse 76, 81541 Munich, Germany

email: rangelov@phys.uni-sofia.bg

A broadband technique for robust adiabatic rotation and conversion of light polarization is proposed. It uses the analogy between the equation describing the polarization state of light propagating through an optically anisotropic medium and the Schrödinger equation describing coherent laser excitation of a three-state atom. The proposed technique is analogous to the stimulated Raman adiabatic passage (STIRAP) technique in quantum optics; it is applicable to a wide range of frequencies and it is robust to variations in the propagation length and the rotary power.

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THREE DIMENSIONAL COMPUTATIONS OF STRONG FIELD DISSOCIATION AND CONTROL

M. Shapiro

Dept. of Chemistry, The University of British Columbia, Vancouver V6T1Z1, Canada

email: mshapiro@chem.ubc.ca

We present a new technique for performing three dimensional computations of photodissociation in strong laser fields and use it to explain the kinetic energy distribution in the $H_2^+ \rightarrow H + H^+$ process, as well as to the spatial separation of chiral molecules by strong laser fields.

ENTANGLEMENT AND TOPOLOGICAL ORDER IN SELF-DUAL CLUSTER STATES

W. Son

Center for Quantum Technology, National University of Singapore, 117542 Singapore, Singapore

email: sonwm@daum.net

We study a Hamiltonian system describing a three-spin 1/2 cluster like interaction competing with an Ising-like exchange. We show that a cluster state, the ground state of the Hamiltonian in the absence of the Ising term, is provided by a hidden order of topological nature. In the presence of the cluster and Ising couplings, a continuous quantum phase transition occurs in the system, directly connecting a local broken symmetry phase to a cluster phase with the hidden order. At the critical point the Hamiltonian is self-dual. We analyze the geometric entanglement and demonstrate that it can capture the transition, as a single parameter.

COMPLETE POPULATION TRANSFER IN 4-LEVEL SYSTEMS VIA PYTHAGOREAN TRIPLE COUPLING

H. Suchowski

Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel

email: fehaim@weizmann.ac.il

I will present an analytical solution of the Schrodinger equation in four level systems. A natural extension of the known Rabi solution in two-level systems will be shown, where instead of one generalized (Rabi) frequency that governs the two level case, two distinct generalized frequencies dictate the four mode dynamics. I will also show how Pythagorean triples, which are the set of three integer numbers $(a; b; c)$, satisfying the Pythagorean equation $a^2 + b^2 = c^2$, are found to play a significant role in the requirements of complete population transfer in a four-level system. The application of this solution to several classical and quantum problems will be discussed as well.

CAN ELECTROSTATIC FIELD LEAD DIRECTLY TO LIFTING OF ENERGY SPIN DEGENERACY?

T. G. Tenev[1] and N. V. Vitanov[1]

Department of Physics, Sofia University, 5 James Bourchier Blvd, 1164 Sofia, Bulgaria

email: tenev@phys.uni-sofia.bg

There are two well known mechanisms which lead to lifting of energy spin degeneracy of single electron systems – magnetic field and spin-orbit coupling. We explore the possibility for existence of a third mechanism in which electrostatic field can lead to lifting of spin-degeneracy directly without the mediation of spin-orbit coupling.

INTRAMOLECULAR ENERGY TRANSFER IN PYRAZINE BY PARTITIONING TECHNIQUE: A TIME-DEPENDENT PERSPECTIVE

I. Thanopoulos, P. Brumer[2] , and M. Shapiro[3]

[1]Theoretical and Physical Chemistry Institute, National Hellenic Research Foundation, Athens 11635, Greece

[2]Chemical Physics Theory Group, Department of Chemistry, and Center of Quantum Information and Quantum Control, University of Toronto, Toronto, Ontario M5S 3H6, Canada

[3]Departments of Chemistry and Physics, The University of British Columbia, Vancouver V6T1Z1, Canada and Department of Chemical Physics, The Weizmann Institute, Rehovot 76100, Israel

email: ithano@eie.gr

We investigate the intramolecular energy transfer dynamics of the S_2 excited electronic state of pyrazine due to radiationless transitions to energetically lower-lying singlet electronic states. The femtosecond decay of S_2 to the S_1 excited state and the picosecond decay of S_2 to the ground electronic state S_0 are studied within an efficient methodology for computing the intramolecular energy transfer dynamics in multi-dimensional configurational spaces. Our method is based on partitioning the full configuration space into the (small) subspace of interest $\mathcal{Q}$, and the rest, the subspace $\mathcal{P}$. The exact equations of motion for the states in $\mathcal{Q}$, under the influence of $\mathcal{P}$, are derived in the time-domain in form of a system of integro-differential equations. Their numerical solution is readily obtained when the $\mathcal{Q}$ space is consisting of just a few states. Otherwise, the integro-differential equations for the states in $\mathcal{Q}$ are transformed into a (larger) system of ordinary differential equations, which can be solved by a single diagonalization of a general complex matrix. The former approach is applied to the investigation of the picosecond $S_2 \longrightarrow S_0$ energy transfer dynamics and the latter is applied to the study of the ultrafast $S_2 \longrightarrow S_1$ decay dynamics.

ULTRAFAST CHARGE TRANSFER DYNAMICS AFTER PHOTO-IONIZATION ON THE NANOSCALE

I. Thanopoulos

Theoretical and Physical Chemistry Institute, National Hellenic Research Foundation, Athens 11635, Greece

email: ithano@eie.gr

We investigate the ultrafast charge transfer dynamics after photo-ionization of an outer-valence electron on a C_{60}-pyrene hybrid compound. We study the cationic charge density evolution during the first few femtoseconds after photo-ionization within one-particle theory, including post-Hartree- Fock corrections. We observe a partial charge flow from the C_{60} towards the pyrene unit of the light-harvesting compound within about 3 femtoseconds after ionization. The charge flow appears oscillatory with a period strongly dependent on the level of post-HF theory used.

SMOOTH COMPOSITE PULSES IN COHERENT ATOMIC EXCITATION

B. T. Torosov[1,2], N. V. Vitanov[1]

[1]Department of Physics, Sofia University, 5 James Bourchier Blvd, 1164 Sofia, Bulgaria

[2]ICB, Université de Bourgogne, UMR CNRS 5209, Dijon, France

email: torosov@phys.uni-sofia.bg

Excitation by composite pulses is routinely used in nuclear-magnetic-resonance experiments, in order to achieve excitation profiles with prescribed shapes [1,2]. The method consists of applying several consecutive pulses with appropriate relative phases. In such way one can achieve a robust analog of the traditional resonance pulses. This technique is, however, mainly developed for pulses with rectangular temporal shape.

In this work we show that composite pulses with smooth temporal shape can be used to obtain analogues of the π-pulses with arbitrarily flat excitation profile. The transition probability can be made robust against variations in the pulse area and/or the detuning. As the number of pulses increases, the excitation profile becomes increasingly insensitive (flat) to small deviations. In order to achieve this, we use the well-known analytic solution of the Rosen-Zener model [3], which assumes a hyperbolic-secant pulse shape and a constant detuning:

$$\Omega(t) = \Omega_0 \text{sech}(t/T), \quad \Delta(t) = \Delta_0, \tag{2}$$

where $\Omega(t)$ is the Rabi frequency, and Ω_0, Δ_0 and T are constant parameters. We calculate the total propagator by multiplying the phased propagators for each pulse. Then we take the Taylor expansion of the full propagator and nullify the first few terms in the respective series (vs. the pulse area deviation or vs. the detuning). The more composite pulses we use, the more terms we are able to nullify, and the more flat the profile will be.

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SINGLE PHOTONS MADE-TO-MEASURE

G. S. Vasilev[1,2], D. Ljunggren[2,3], A. Kuhn[2],

[1]Department of Physics, Sofia University, 5 James Bourchier Blvd, 1164 Sofia, Bulgaria

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

[3]Dept. of Applied Physics, KTH - Royal Institute of Technology, 106 91 Stockholm, Sweden

email: gvasilev@phys.uni-sofia.bg

We investigate the efficiency of atom-cavity based photon-generation schemes to deliver single photons of arbitrary temporal shape. Our model applies to Raman transitions in three-level atoms with one branch of the transition driven by a laser pulse, and the other coupled to a cavity mode. For any possible shape of the single-photon wavepacket, we derive an unambiguous analytic expression for the shape of the required driving laser pulse. We furthermore discuss the constraints limiting the maximum probability for emitting any desired photon, and use these to estimate upper bounds for the efficiency of the process. The model is not only valid for Vacuum-Stimulated Raman Adiabatic Passages (V-STIRAP) in the strong-coupling and bad-cavity regime, but it generally allows controlling the coherence and population flow in any Raman process.

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MODE ENTANGLEMENT IN QUANTUM INFORMATION PROCESSING

V. Vedral

Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK

email: vlatko.vedral@gmail.com

Natural particle-number entanglement resides between spatial modes in coherent ultra-cold atomic gases. However, operations on the modes are restricted by a superselection rule that forbids coherent superpositions of different particle numbers. This seemingly prevents mode entanglement being used as a resource for quantum communication. In my talk I will argue that mode entanglement of a single (massive or massless) particle can be used for dense coding and quantum teleportation despite the superselection rules. I will present schemes where the dense coding linear photonic channel capacity is reached without a shared reservoir and where the full quantum channel capacity is achieved if both parties share a coherent particle reservoir. If time permits, I will discuss the type of non-locality arising from mode entanglement. For instance, one photon superposed symmetrically over many distant sites (i.e. in a W state) can give an "all or nothing" violation of local realism (in a similar manner to the GHZ state). This shows that mode entanglement is as viable and useful as any other form of entanglement exploited in experimental physics.

ROBUST MICROWAVE DRESSED STATES WITH TRAPPED IONS

C. Wunderlich

Fachbereich Physik, Universität Siegen, 57068 Siegen, Germany

email: wunderlich@physik.uni-siegen.de

Laser cooled atomic ions confined in an electrodynamic cage have been very successfully used for quantum information processing. Recently, laser-less addressing of ions and Magnetic Gradient Induced Coupling (MAGIC) between ion spins and their motion using rf radiation (prerequisite for conditional quantum dynamics with trapped ions) has been demonstrated for the first time [1]. Using MAGIC, several technological and fundamental hurdles on the path towards a scalable trapped ion quantum simulator may be overcome. An issue that remains is the necessity to use magnetic field sensitive states that are susceptible to ambient noise fields limiting their coherence time. Here, we report on experiments with Yb+ ions showing that the use of microwave dressed states may enhance the coherence time of these states by up to two orders of magnitude. Dresses states were prepared and probed using a modified STIRAP sequence.

1. M. Johanning, A. Braun, N. Timoney, V. Elman, W. Neuhauser, Chr. Wunderlich, Phys. Rev. Lett. **102**, 073004 (2009).

COHERENT PHENOMENA IN THE VICINITY OF METALLIC NANOSTRUCTURES

V. Yannopapas

Department of Materials Science, University of Patras, Panepistimioupolis, GR-26504, Rio, Greece

email: vyannop@upatras.gr

The interaction of light with atoms which are located closed to metallic nanostructures enables the observation of phenomena in quantum optics which cannot be unreeled when atoms are in vacuum. Such a case is the observation of quantum interference of the spontaneous emission paths of a V-type three-level atom. When such an atom is placed in the vicinity of properly designed metallic nanostructure, the quantum interference can be greatly enhanced around the surface-plasmon bands of the metallic nanostructure leading to much slower decay of the excited atomic state [1]. Besides this, we present two characteristic examples of analogues of well established quantum coherent phenomena in classical electromagnetism. The first is a classical analogue of electromagnetically-induced transparency. Namely, we will examine the case of a two-dimensional lattice of metallic nanoparticles on top of a guiding substrate. If the substrate supports guided modes which fall within the surface-plasmon absorption band of the lattice of nanoparticles then one can quench light absorption via a mechanism which resembles electromagnetically-induced transparency in atomic gases [2]. Alternatively, the substrate can make metal absorb light in spectral regions well above the surface-plasmon band where metal is essentially transparent. The second analogue is about the coherent control of the optical near-field in nanostructures. Namely, we will show that one can achieve spatio-temporal control over the excitation of surface exciton-polaritons in semiconductor nanoparticles by a proper choice of a chirped light pulse [3]. This is achieved in nanoparticles made from semiconductors with strong excitonic oscillator strength and small absorption linewidth such as copper chloride or oxide.

1. V. Yannopapas, E. Paspalakis, and N. V. Vitanov, Phys. Rev. Lett. **103**, 063602 (2009).

2. V. Yannopapas, E. Paspalakis, and N. V. Vitanov, Phys. Rev. B **80**, 035104 (2009).

3. V. Yannopapas and N. V. Vitanov, Phot. Nanostr., submitted.

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CAMEL VI Programme

	June 29	June 30	July 1	July 2
09:00 – 09:40	Lange	Vedral	Halfmann	Hensinger
09:40 – 10:10	Peters	Oreshkov	Comparat	Ohberg
10:10 – 10:40	Himsworth	Suchowski	Entin	Caruso
10:40	coffee	coffee	coffee	coffee
11:10 – 11:50	Guerin	Garraway	Wunderlich	Bruner
11:50 – 12:20	Son	Maniscalco	Dantan	Thanopoulos
12:20 – 12:50	Pashov	Andersson	P. Ivanov	Yannopapas
12:50	lunch	lunch	lunch	lunch
			excursion	
16:30	coffee	coffee		coffee
17:00 – 17:40	Chatel	Pruvost		Gerdjikov
17:40 – 18:00	Vasilev	Gavenda		Praxmeyer
18:00 – 18:20	Gogyan	Lazarou		Mazzola
18:20 – 18:40	Laine	Münch		Torosov
20:00	**posters**	**Shapiro***	**conf. dinner***	
	Azizbekyan			
	Boradjiev			
	Dridi			
	Genov			
	Hakobyan			
	S. Ivanov			
	Pruvost			
	Rangelov			
	Tenev			
	Thanopoulos			

*Special after-dinner lecture

*The conference dinner will be held in the garden of Grand hotel Varna.