Ion-photon entanglement and state mapping in an optical cavity

Andreas Stute, Bernardo Casabone, Birgit Brandstätter, Konstantin Friebe, Klemens Schüppert, Philipp Schindler, Thomas Monz, Piet O. Schmidt, **Tracy E. Northup** (University of Innsbruck) and Rainer Blatt

A quantum network requires information transfer between distant quantum computers; the transfer process can be either heralded (probabilistic) or deterministic. Using a single calcium ion coupled to two orthogonal polarization modes of a high-finesse optical resonator, we demonstrate building blocks of both heralded and deterministic networks.

First, we show on-demand entanglement between an ion and a photon, generating maximally entangled states with fidelities up to (97.4±0.2)% [1]. Both amplitude and phase of the entangled state are fully tunable due to the use of a bichromatic Raman field, and the phase of the entangled state is independent of the photon detection time. Ion-photon entanglement, generated simultaneously at remote nodes, is the basis for remote ion-ion entanglement schemes [2].

Next, we map a quantum superposition state of an ion onto a cavity photon with process fidelity of (92±2)%. The time independence of the mapping process allows us to characterize the interplay between process fidelity and efficiency. A direct application of this scheme is deterministic state transfer between two remote quantum nodes [3,4].

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Dynamical decoupling sequences for realizing robust quantum gates and memories with trapped ions

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Dynamical decoupling (DD) is a widely used technique in the framework of nuclear magnetic resonance to protect the coherence of quantum systems against a detrimental environment. DD pulse sequences can be used to enhance the coherence time of quantum memories and the fidelity of quantum gates. However, imperfections of pulses may destroy quantum information or interfere with gate dynamics. We investigate different sequences with respect to their capability to suppress decoherence while still being robust against pulse imperfections in an ion trap experiment. Our results obtained with $^{171}Yb^{+}$ ions demonstrate that sequences based on varying phases are self-correcting. We found sequences that allow for the implementation of a conditional quantum gate even if the gate time is more than one order of magnitude longer than the coherence time of the system.

Investigation of an atom-ion quantum hybrid system

Lothar Ratschbacher (University of Cambridge), Christoph Zipkes, Carlo Sias, Michael Köhl

Hybrid quantum experiments with single ions immersed in quantum gases are starting to be used as versatile systems for experiments in quantum information science, atomic physics and cold chemistry.

We deterministically position radio-frequency trapped $^{174}Yb^{+}$ ions inside a Bose Einstein condensate of ^{87}Rb atoms and achieve independent control on the motional and internal states of both species. We investigate the fundamental atom-ion interactions by characterizing elastic and inelastic collisions and measure their energy-dependent reaction rate constants. In the presence of near resonant light interactions between both species are strongly modified, leading to inelastic scattering rates that are more than three orders of magnitude higher compared to collisions in the ground states. We analyze the process at the single particle level with ion trap mass spectroscopy to identify the underlying interaction channels.

In order to assess their potential use for quantum information science we furthermore study the coherence properties of spin qubits in the atom-ion hybrid system. The emerging understanding of the state-dependent interactions between the two quantum systems will pave the way for applications in quantum information science and cold-matter research.

Schrödinger cat state spectroscopy with trapped ions

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Trapped and laser-cooled ions have excellent properties for high-precision spectroscopy. By quantum logic spectroscopy, ions whose internal state cannot be detected easily can be read out via a second ion species trapped together with the spectroscopy ion. In this poster, we discuss the use of geometric phases for a particular type of quantum logic spectroscopy that can be used to detect the absorption or emission of single photons with high detection efficiency. By preparing a Schrödinger cat state of a two-ion crystal where the ions's motion is entangled with the internal states of the logic ion, a photon scattered by the spectroscopy ion manifests itself by a geometric phase that can be subsequently read out via the logic ion. This measurement scheme is applied to a mixed ion crystal of two calcium isotopes.

High-resolution spectroscopy of trapped HD^+ molecular ions

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Cold trapped molecules currently represent an intense field of activity requiring appropriate methods of molecule production, translational and internal cooling, spectroscopy and sensitive detection. Many applications, such as chemical reaction studies, tests of molecular quantum theory, fundamental physics and quantum computing would benefit strongly from availability of advanced manipulation techniques, already standard in atomic physics. These are not straightforward for molecules, and for charged molecules have not yet been demonstrated [1].

We demonstrate addressing of individual hyperfine states of ro-vibrational levels by excitation of individual hyperfine transitions, and controlled transfer of population into a selected hyperfine state. We use molecular hydrogen ions (HD^+) as a model system and employ a novel frequency-comb-based, continuous-wave 5 μm laser spectrometer [2]. To our knowledge, the achieved spectral resolution (3 MHz) is the highest obtained so far in the optical domain on a molecular ion species [3].

As an application of the technique, we perform a test of the ab-initio theory of the molecular hydrogen ion [3]. Measured hyperfine structure splittings are found to be in agreeement with the ab-initio calculation within the experimental uncertainty. The spin-less transition frequency has been measured with an accuracy of 1 ppb, with a 2 sigma deviation from the ab-initio theory value.

We also report on the first observation of the fundamental pure rotational transition in this molecule [4].

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Simulation of driven open quantum systems with trapped ions.

Philipp Schindler (University of Innsbruck), Markus Müller, Daniel Nigg, Julio Barreiro, Thomas Monz, Michael Chwalla, Markus Hennrich, Sebastian Diehl, Peter Zoller, Rainer Blatt

Simulating interacting many-particle quantum-systems on a classical computer is in general inefficient as the required resources increase exponentially with the system size. Therefore the simulation of quantum dynamics with the aid of another, well-controlled quantum system has gained a lot of attention in the last few years. Generally two approaches for quantum simulators are explored. In the analog approach the Hamiltonian of the system of interest is directly implemented in the simulator system. This means that only systems with the same Hamiltonian as the simulator can be covered, but the requirements on the control are less stringent. In the digital approach, the dynamics is split in small discrete steps, which can be implemented efficiently. This leads to time dynamics with small systematic but bounded errors from the ideal continuous dynamics. For this approach, a universal quantum information processor is required which also implies that a faithful simulation is expected to be possible based on the toolbox provided by quantum error correction.

Most current quantum simulators replicate closed quantum systems governed only by coherent dynamics. However, it seems natural that large systems need to be treated as open systems, which are even harder to simulate on a classical computer. Building a quantum simulator for arbitrary open systems is challenging because in addition to a tremendous amount of control over the system, a well-controlled coupling to the environment is necessary. Recently, a proof of principle experiment of this coupling was demonstrated in our ion trap quantum information processor. Dissipative many-body dynamics can then be realized by entangling an additional auxiliary qubit with the remaining quantum register and subsequent controlled dissipation of this qubit. With the aid of these tools it was possible to prepare an entangled four-qubit state from a completely mixed state using only dissipative interactions.

Recently, our group also demonstrated the building blocks for a universal closed-system digital simulator by digitally simulating the time evolution of various interacting spin models for system sizes up to six particles. In this work we apply coherent and dissipative techniques in a combined way, to simulate the dynamics of an open and interacting many-body spin system, which shows a variety of novel non-equilibrium effects. Recently, a many-body system of bosons was studied theoretically, and it was shown how tailored dissipative dynamics can drive the system into a superfluid steady-state. It was predicted that the system should undergo a non-equilibrium phase transition as coherent dynamics is applied, which is incompatible with the steady state of the dissipative dynamics. It was shown how increasing the strength of coherent interactions leads to a transition from the superfluid phase to a thermal state. Here, we show how to map this bosonic system onto our ion-trap quantum simulator and demonstrate the interplay between dissipative and coherent dynamics in a small system. Since the dynamics requires many quantum operations, the errors induced by performing the gates play a major role. Universal quantum error correction protocols are very costly. We therefore develop and benchmark error detecting and correcting methods tailored to the simulated system.

Design of a cold nanoparticle source for matter wave interference experiments

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Matter wave interference is a tool that allows probing the quantum nature of particles in the gas-phase. Atom interferometry is a well-established technique [1] and also beams of complex molecules could already be used to probe the foundations of physics [2] and to determine molecular properties by quantum metrology [3].

An important challenge in new quantum experiments is now the generation of cold samples of neutral, large molecules, clusters or nanocrystals in the gas phase. Matrix assisted laser desorption (MALDI) [4] and metal cluster sputter sources [5] are well established tools for the preparation of singly charged gas-phase ions even in the excess of 1 MDa [6]. Quantum interferometry profits from the preparation of neutral mass selected particles beams, which still proves to be challenging, especially if the nanoparticles need to be internally cold and slow (T ~ 10 K).

We will present the **V**ienna **I**on **T**rap for **M**olecular **I**nterference **E**xperiment (VITAMIN-E), which aims at preparing such samples: A cryogenic buffer gas loaded ion trap is filled by laser desorption with negatively charged ions. Upon cooling neutral molecules are obtained from the internally and externally cold ions by post-neutralization via laser detachment.

We discuss the current status of this dedicated ion trap setup and introduce ideas for loading, trapping and detecting such cold and neutral particles beams.

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Light with orbital angular momentum interacting with trapped ions

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We study the interaction of light beams carrying angular momentum with a single, trapped and well localized ion. We provide a detailed calculation of selection rules and excitation probabilities for quadrupole transitions. The results show the dependencies on the angular momentum and polarization of the laser beam as well as the direction of the quantization magnetic field. In order to optimally observe the specific effects, focusing the angular momentum beam close to the diffraction limit is required. We discuss a protocol for examining experimentally the effects on the S1/2 to D5/2 transition using a 40 Ca+ ion. Various applications and advantages are expected when using light carrying angular momentum: In quantum information processing, where qubit states of ion crystals are controlled, parasitic light shifts could be avoided as the ion is excited in the dark zone of the beam at zero electric field amplitude. Such interactions also open the door to high dimensional entanglement between light and matter. In spectroscopy one might access transitions which have escaped excitation so far due to vanishing transition dipole moments.

Observing a single photon entangles two ions

Lukas Slodicka (University of Innsbruck), Gabriel Hetet, Nadia Röck, Philipp Schindler, Markus Hennrich, Rainer Blatt

The generation of entanglement between distant physical systems is an essential primitive for quantum communication networks and further tests of quantum mechanics. The realization of heralded entanglement between distant atomic ensembles was amongst the first major achievements in this direction. Probabilistic generation of heralded entanglement between single atoms was demonstrated using single trapped ions with an entanglement generation rate given by the probability of coincident detection of the two photons coming from the ions. More recently, single neutral atoms trapped at distant locations were entangled by first generating the single atom-photon entanglement and then mapping the photonic state on the electronic state of the second atom. A heralding mechanism will however be essential for efficient entanglement and scalability of quantum networks using realistic channels, and single qubit operations are required for distributed quantum information processing schemes. Here, we report on the realization of a fundamental process which fulfills both these conditions by showing entanglement between two well-defined atomic qubits via emission and detection of a single light quanta. In this scheme, both the energy and the phase of the emitted single photon are used for entanglement generation. In addition, this mechanism allows the demonstration of a large speedup in entanglement generation rate compared to the previously realized heralded entanglement protocol with single atoms. This result will enable the practical distribution of quantum information over long distances using single atom architectures.

Towards an ion-cavity system with single Yb^+ ions

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The development of an efficient ion-photon interface is a major challenge which needs to be overcome to realize large scale ion-based quantum networks. Such an interface could consist of a single ion coupled to high finesse optical cavity. Existing ion-cavity systems operate in a regime, where the coupling of light and ion is smaller than the excited state decay rate[1]. In order to enhance the coupling, smaller cavity mode volumes must be used. However, macroscopic mirrors cannot be brought close enough to the ion since uncontrollable charging effects on the dielectric surface would disturb the electric trapping potential.

We report on our ongoing efforts to implement an ion-cavity system operating on the $^3D[3/2]_{1/2}$-$^2D_{3/2}$ (935 nm) transition of Yb^+. The mirrors used for the cavity are directly machined onto the tips of optical fibres to reduce the mode volume while keeping the dielectric surface exposed to the ion small[2]. In order to achieve a high ion excitation rate on the cavity transition a laser system at 297 nm ($^2S_{1/2}$-$^3D[3/2]_{1/2}$ transition) has been built[3]. Besides the absolute frequency measurements of this transition for even isotopes we also show that this light can be used for laser cooling of trapped Yb^+ ions.

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Towards a 3H/3He Mass-Ratio Measurement with THe-Trap

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THe-Trap is a Penning trap mass spectrometer designed to measure the mass-ratio of tritium (3H) to its daughter nuclide helium-3 (3He) with an uncertainty of 10^{-11}, which would improve the present value by a factor of 40 [1]. This mass ratio is relevant for the KArlsruhe TRItium Neutrino experiment (KATRIN) [2], which aims to measure the electron anti-neutrino mass with a sensitivity of 0.2 eV/c^2 (95% c.l.). KATRIN measures the shape of the endpoint region of the beta-decay of 3H. The endpoint with a hypothetical zero mass neutrino can be determined by the mass-ratio. This provides an important systematic check for the KATRIN data.

A dedicated tritium laboratory was built. In that the ambient temperature is stabilized to 0.07 K. The vibration of the cryostat is below 1 µm/s. In addition to other environmental parameters, the magnetic field is monitored and stabilized. This is achieved by stabilizing the pressure and the level of the liquid helium surrounding the traps. The result is a stable temperature of the materials and hence, reduced magnetic field fluctuations due to the temperature dependence of the susceptibility. External field fluctuations are measured by a fluxgate magnetometer and compensated by a pair of Helmholtz coils surrounding the cryostat [3].

THe-Trap [4] combines an external ion source with two hyperbolical Penning traps, yet retaining the possibility to load the traps by ionizing rest gas with electrons from a field emission point inside the trap envelope. External ion loading is expected to minimize the risk of contaminating the trap electrodes with radioactive tritium. By swapping the ions-of-interest (3H, 3He) between the two traps without having to reload the trap, the total measurement cycle will be shortened, thereby reducing the influence of magnetic field drifts. However, the transfer between the two traps through small holes in the endcaps in single-pass mode requires the use of a well-timed sequence of transfer pulses on various electrodes that has yet to be demonstrated. To get an indication of systematic uncertainties a rough mass ratio measurement of 16O6+ to 12C4+ was performed. Details about the experimental setup and recent progress will be given.

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Interfacing single ions and photons via cavity QED

Hiroki Takahashi (University of Sussex), Andrew Riley-Watson, Stephen Begley, Nicolas Seymour-Smith, Elisabeth Brama, Matthias Keller, Wolfgang Lange

Interfacing a flying photonic qubit with a stationary matter qubit is of vital importance in the field of quantum information. Due to their robust trapping and well-established coherent control, trapped single ions are among the most promising candidates as a stationary qubit for quantum network. The need for coherently interfacing single ions and photons naturally leads to cavity QED with single ions, where an optical cavity with small mode volume is used to achieve strong coupling.

At Sussex University, we are currently working on three different ion-cavity QED experiments in each of which a different regime of ion-photon coupling is investigated. In one of them, a cavity collinear to the axis of a linear ion trap is employed where a moderate ion-photon coupling can be achieved. Even though its coupling strength is relatively weak, it can be exploited for probabilistic processes based on entanglement of ions and single photons emitted from the cavity. A pair of ions can be probabilistically entangled by measuring the polarizations of outcoming cavity photons, as the ions are simultaneously interacting with the same cavity field.

Another experiment employs a cavity transverse to the trap axis where smaller mode volume, hence stronger coupling is available. In this case a near-deterministic transfer of quantum states between ions and photons is possible.

Finally the strongest coupling is planned in an experiment employing a miniature fiber cavity. The fiber cavity is tightly integrated in an endcap-type ion trap and well shielded by the design, avoiding possible adverse effects from the dielectric surfaces close to a trapped single ion. In a prototype of this system, we have efficiently captured the fluorescence of a single calcium ion, observed its non-classical g(2) function and produced pulsed single photons on demand. We will review our three ion-cavity QED experiments and report on their updated status.

Relativistic effects for spin splitting of neutral particles and their trapped ion emulation

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We have explored the properties of spin splitting for neutral particles possessing electric and magnetic dipole moments propagating in electromagnetic fields. We have found two notable features of the spin splitting and the associated Larmor precession which are consequences of special relativity. First we report the existence of upper limit of spin splitting equal to twice the rest energy for the particle and corresponding upper limit for the Larmor precession frequency. Second we predict the noninvariance of the spin splitting and the corresponding Larmor frequency with respect to Lorentz boosts which bears resemblance to the Doppler effect. As way of experimental verification we have proposed their emulation in trapped ions.

Small crystals in a Penning trap

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We trap small Coulomb crystals of calcium ions in a Penning trap. Unlike in RF traps, ions in a Penning trap do not suffer any micromotion at any position inside the trapping volume.

We use a 1.8 T superconducting magnet to provide radial confinement, and apply an electric field to a set of cylindrical electrodes to confine the ions axially.

Optical access is challenging; we image florescence via a narrow gap between the vacuum chamber and the inner wall of the magnet bore. Despite this and other difficulties, we have resolved individual ions in a crystal using an amplified CCD.

One of the two radial modes of motion, the magnetron motion, is unstable and requires an additional small RF field to couple it to the modified cyclotron motion so that laser cooling is efficient. The crystal is expected to rotate around the magnetic field at half the cyclotron frequency, $eB/2m \approx 350 \times 2\pi\,\text{kHz}$, when locked to this RF drive.

In our trap we have two laser beams which propagate along the radial and axial directions to give sufficient cooling to crystallise up to 10 ions along the axis. Previous experiments have shown that where an axial beam is not present we could only crystallise 2 ions along the magnetic field axis [1]. By varying the axial confining potential and the amplitude of the additional RF field, we can manipulate small crystals into different shapes, as described theoretically in [2]. We are currently characterising the frequencies of the trap and mapping the family of crystal shapes which are visible.

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Experimental and theoretical studies of planar zigzag ion crystals

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Since several years cold ion crystals trapped in linear Paul traps[1] are one of the systems for fundamental studies in the field of quantum information processing. With the help of zigzag ion crystals[2,3] this system can be used for quantum simulations[4,5] of frustrated spin systems[6,7] and quantum fluctuations, whereupon the planar zigzag configuration allows the observation and addressing of all ions. We present measurements of the positions of 3 to 19 ions in a crystal in zigzag configuration with sub micron precision. Meanwhile the radial trap frequency was changed from 160 to 330 kHz. We were able to directly compare our measurements with simulations of the zigzag transitions. In addition the critical anisotropy parameter $\alpha_{1,2}$ and the eigenmodes and frequencies of the zigzag modes were measured and calculated.

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ECTI 2012

Obergürgl, Austria 10-14 September

Authors: Jonathan Pinder, Ashley Jeens, José L.Verdú

Title: Quantum circuits with geonium atoms

Abstract:

At the University of Sussex we are building a coplanar-waveguide (CPW) Penning trap. This is a novel planar Penning trap, which results form the projection of the well-known cylindrical trap onto the surface of a chip [1]. The trap allows for the compensation of electrical anharmonicities up to the sixth order and permits the observation of a single trapped electron, a primary goal not yet achieved with planar Penning trap technology. The electron can be coupled to a distant superconducting coplanar-waveguide resonator, such as those used in circuit-QED with artificial two level systems. The cyclotron motion interacts coherently with the microwave resonator, implementing a system of two coupled quantum harmonic oscillators and with applications in quantum metrology and quantum computation. In the poster, we report on recent experimental progress in the construction of a cryogenic CPW-Penning trap.

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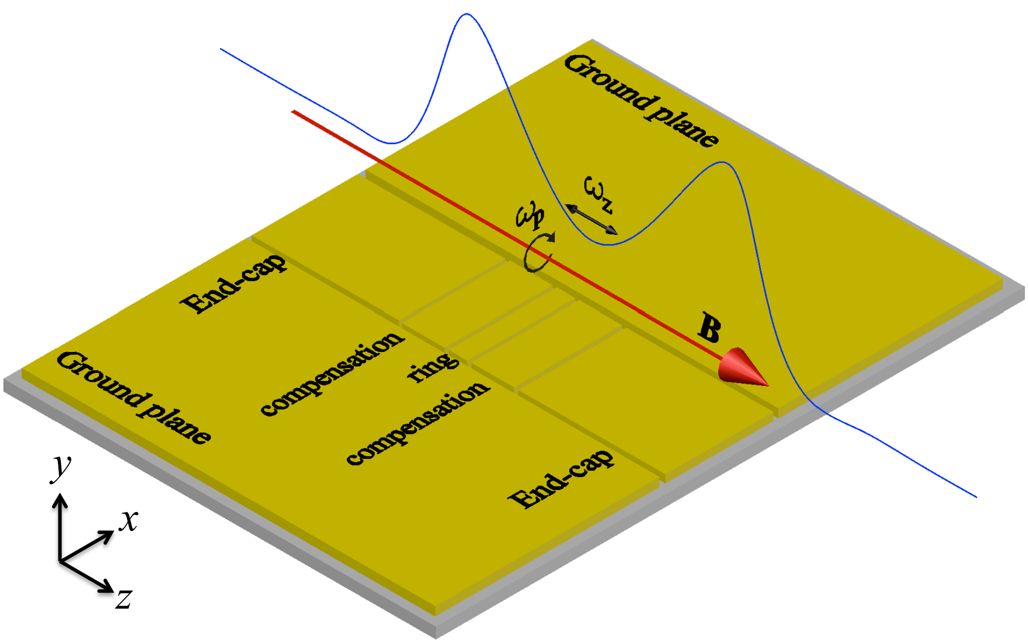

Sketch of the coplanar-waveguide Penning trap developed at Sussex

High-fidelity quantum information processing with composite pulse sequences

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The technique of composite pulses, developed originally in polarization optics and nuclear magnetic resonance (NMR), is a powerful tool for quantum state manipulation. This technique replaces the single pulse used traditionally for driving a two-state quantum transition by a sequence of pulses with suitably chosen phases, which are used as a control tool for shaping the excitation profile in a desired manner. This technique combines the accuracy of resonant excitation with a robustness similar to adiabatic techniques. We have developed a simple systematic approach, which allows the construction of composite sequences of pulses with smooth shapes and time-dependent detuning that can create ultrahigh-fidelity excitation profiles. Our method uses the SU(2) representation of the propagator of the two-state system, instead of the commonly used intuitive Bloch SO(3) rotations. We have designed arbitrarily accurate broadband, narrowband, passband and fractional-pi composite pulses. In one of the applications, composite sequences can reduce dramatically the addressing error in a lattice of closely spaced atoms or ions, and at the same time greatly enhance the robustness of qubit manipulations. One can thus beat the diffraction limit, for only atoms situated in a small spatial range around the center of the laser beam are excited.

We have used composite sequences of chirped pulses to optimize the technique of adiabatic passage between two quantum states: composite adiabatic passage (CAP), in which nonadiabatic losses can be canceled to any desired order. We have also used composite pulses to design new, more efficient implementations of highly-conditional quantum gates with trapped ions, such as Toffoli's CC-NOT gate. We have designed also composite pulse sequences suitable for manipulation of multistate systems. These sequences allow to suppress dynamically unwanted transition channels in complex systems with branched linkage patterns even when the relevant couplings are unknown. Compensation with respect to simultaneous deviations in polarization, pulse area, and detuning is demonstrated.

Quantum Imaging with Independent Light Sources

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Multi-photon interferences with indistinguishable photons from independent light sources are at the focus of current research due to their potential in quantum metrology, entanglement of remote particles and optical quantum computing [1–3]. The paradigmatic states for multi-photon interference are the highly entangled NOON states which can be used to achieve enhanced resolution in interferometry and lithography [4]. However, multi-photon interferences from independent uncorrelated emitters can also lead to enhanced resolution [5]. So far, such quantum interferences have been observed with maximally two independent emitters, like trapped ions, atoms, quantum dots, molecules or classical sources [6–11].

Here we report the measurement of quantum interferences of photons emitted by up to five independent emitters [12]. We observe the multi-photon interference patterns using thermal light sources (TLS) and compare the corresponding signals to those obtained with single photon emitters (SPE). It is shown that for equal numbers of emitters and detectors at particular *magic positions* $\mathbf{r}_2, \ldots, \mathbf{r}_N$ the normalized Nth order spatial intensity correlation function $g^{(N)}(\mathbf{r}_1, \ldots, \mathbf{r}_N)$ as a function of $\mathbf{r}_1$ displays an interference pattern of the form $g^N(\mathbf{r}_1) \propto 1 + V_0^{(N)} \cos[(N-1)\delta(\mathbf{r}_1)]$, where $\delta(\mathbf{r}_1)$ and $V_0^{(N)}$ are the relative phase accumulated by photons from adjacent emitters towards the detector at $\mathbf{r}_1$ and the visibility of the correlation signal, respectively. This modulation exhibits a fringe spacing equivalent to those of NOON states with $N-1$ photons.

A detailed quantum field theoretical description allows to identify each quantum path contributing to the N-photon signal. It is shown that, apart from an offset, for N TLS the same interference terms contribute to the multi-photon signal than those obtained from N SPE. In particular, for the magic detector positions, the multitude of N-photon quantum paths lead for both, TLS and SPE, to a NOON-like modulation oscillating at the highest possible spatial frequency of the light emitting structure, all other terms cancelling out by destructive interference or adding to the background of the signal. In this way, for $N > 2$, it is possible to obtain a gain in resolution in imaging the source which overcomes the canonical classical resolution limit. The measurement can be considered an extension of the experiment by Hanbury Brown and Twiss who investigated intensity correlations up to second order [13]. Here we go beyond this level by measuring spatial intensity correlations up to fifth order.

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Precision mass measurement of ^{54}Ca solves long-standing dispute about nuclear structure

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State-of-the-art precision measurements on radioactive ions have been performed at the Penning-trap mass spectrometer ISOLTRAP at CERN. Minute production rates and millisecond half-lives pose enormous challenges on the experimental setup and often require new experimental techniques. The ISOLTRAP setup has recently been enhanced with an electrostatic mirror trap acting as a multi-reflection time-of-flight (MR-ToF) mass separator. This device is especially suited for mass measurements under the above conditions and still provides an accuracy sufficient to answer nuclear-structure and astrophyiscal questions.

The calcium isotopic chain is an ideal test case for nuclear-structure evolution at the limits of existence. Since nuclear models used for predicting the structure of exotic nuclei have been developed and fitted to stable nuclei, it is highly questionable whether they can produce, e.g., the correct shell closures far from stability.
The recent measurements on neutron-rich calcium isotopes up to ^{54}Ca are compared with predictions made by models which utilize three-body nuclear forces, where we find an excellent agreement. These results unambiguously establish the energetic ordering of quantum states and help to predict masses at the drip line, which is critical for the successful modelling of astrophysical processes.

Microfabricated ion trap chips for quantum technologies

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Precise control of trapped ion strings has resulted in significant experimental advances in quantum information processing, quantum simulation and quantum metrology [1]. Ion trap arrays are a suitable architecture [2] for progressing towards larger systems of qubits. Although 2D electrode arrays [3] are popular due to their relative ease of fabrication, 3D trap geometries are the optimal configuration for creating a superior trapping potential.

Following our earlier design [4], we describe the operation of a novel ion microtrap linear array etched from a silica-on-silicon wafer [5,6]. The device uniquely combines the advantages of a 3D electrode geometry, with the scalability, resolution and precision of semiconductor microfabrication techniques, to create a trap array in a monolithic chip. Confinement of $^{88}Sr^{+}$ ions over a wide range of the trap stability parameter, and radial motional frequencies in excess of 4 MHz, have been observed. The 3D geometry yields a deep (several eV) and efficient trapping potential. The electric field noise spectral density, $S_E(\omega)$, resulting in anomalous heating of ion motion, was measured. Scaled by the motional frequency, ω, the value $\omega S_E(\omega)$ is the lowest reported for room temperature scalable architectures, resulting in long ion storage times. Spectroscopy of the 5s $^2S_{1/2}$ – 4d $^2D_{5/2}$ optical qubit transition in a single ion shows confinement in the Lamb-Dicke limit. Measured operating characteristics indicate that the microtrap is suited to the creation and control of entangled states.

Our first applications for the device are planned in quantum metrology including quantum sensors and optical clocks. We present new designs, presently under fabrication, where we take advantage of improved manufacturing steps for an increased yield. The new designs include separate loading and operation regions. This will be combined with a fully masked atom source setup for clean ion trap loading to enable long term operation of the trap without degradation in performance due to atom vapour deposition. The atom source is designed to fit into our compact and versatile electronic and UHV setup [7] and suitable for extension to multi-species loading. An improved laser system with full control of phase, frequency and amplitude set up to enable entangling operations is nearing completion. Near future plans include, multi-ion string initialisation in the motional and internal ground state, coherent shuttling operations verified with Ramsey spectroscopy and realisation of a 2 ion Mølmer-Sørensen gate [8].

Beyond this, the fabrication process enables scaling to larger and more complex arrays, as well as integration of photonic components into the chip. An integrated fibre-cavity and trap system seems possible, thus showing a route towards a quantum network of interconnected ion trap processors.

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