University of Sussex
Department of Physics & Astronomy

IQsim13

Quantum Simulations with Trapped Ions, 2013

BOOK of ABSTRACTS

This workshop is supported via the European COST action IOTA and the South East Physics Network (SEPnet).

IQsim13

Quantum Simulations with Trapped Ions, 2013

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Old Ship Hotel, Brighton

Organising Committee

Winfried Hensinger (University of Sussex)

Diego Porras (University of Sussex)

This workshop is supported via the European COST action IOTA and the South East Physics Network, SEPnet.

Hosted by the University of Sussex, Department of Physics & Astronomy,

Workshop Themes

Trapped ions are an extremely powerful system for the implementation of quantum simulations.

In this workshop we will discuss the following key elements:

- Experimental implementations of quantum simulations with trapped ions
- Theoretical ideas for quantum simulations with trapped ions
- Architectures for quantum simulations with trapped ions
- Entanglement generation and coherent evolution in trapped ion quantum simulators.

IQSim13 website

http://www.sussex.ac.uk/amo/iqsim13/

Workshop Proceedings

The talks will be published on the IQsim13 webpages.

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Talks

CONTROLLING AND MEASURING QUANTUM TRANSPORT OF HEAT IN TRAPPED-ION CRYSTALS

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ABSTRACT

Measuring heat flow through nanoscale systems poses formidable practical difficulties as there is no `ampere meter' for heat. We propose to overcome this problem by realizing heat transport through a chain of trapped ions. Laser cooling the chain edges to different temperatures induces a current of local vibrations (vibrons). We show how to efficiently control and measure this current, including fluctuations, by coupling vibrons to internal ion states. This demonstrates that ion crystals provide a suitable platform for studying quantum transport, e.g., through thermal analogues of quantum wires and quantum dots. Notably, ion crystals may give access to measurements of the elusive large fluctuations of bosonic currents and the onset of Fourier's law. These results are supported by numerical simulations for a realistic implementation with specific ions and system parameters.

FROM QUANTUM CONTROL TO QUANTUM SIMULATION WITH TRAPPED IONS

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ABSTRACT

We describe recent insights into the control of quantum mechanical systems in the time domain as filtering, and how this technique may be applied in the context of quantum simulation. In this work, we develop novel sequences of unitary operations that engineer desired effective Hamiltonians, starting only with an arbitrary native inter-particle interaction and single-qubit addressing. The result is a hybrid programmable analog simulator permitting a broad class of interacting spin-lattice models to be generated. We show how determining the relevant hardware "program" of unitary pulses to implement an arbitrary spin Hamiltonian on such a simulator can be formulated as a linear program that runs in polynomial time and scales efficiently in hardware resources. Our analysis extends from circuit model quantum information to adiabatic quantum evolutions, where our approach allows for the creation of non-native ground state solutions to a computation. Recent progress validating the filter-design formalism in quantum control will be presented using trapped 171Yb+ ions.

GATES, DATA AND LOGIC BUSES THROUGH SPIN CHAINS

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ABSTRACT

In this talk, we describe some possible future applications of the dynamics of excitations in a spin chain in connecting remote registers for scalable quantum information processing. We first present a brief motivation, and a basic scheme to illustrate the idea of quantum state transfer through a spin chain. This is followed by an extremely short outline survey (by no means exhaustive) of the theory to date including recently proposed methods which provides a high fidelity state transfer with minimal engineering, encoding and control. Next we present a couple of protocols for using nonequilibrium dynamics of multiple magnons induced by quenches for establishing entanglement between well separated spins. In context of the Kondo model of an impurity coupled to a spin chain lead, the conversion of its natural ground state entanglement to a useful form through the dynamics will be discussed. Finally the possibility of usage of spin chains for quantum logic between remote registers is discussed along with a specific application to atomic systems.

LIEB-ROBINSON BOUNDS FOR TRAPPED IONS

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ABSTRACT

In this talk I will derive a mathematical bound for the speed with which correlations propagate in a system of spins that interact through the exchange of bosonic particles.

I will discuss how this relates to a typical setup of trapped ions and how such phenomena could be measured in a realistic experiment.

QUANTUM SIMULATION WITH ATOMS AND IONS

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ABSTRACT

In my talk I will present a number of approaches towards quantum simulation of solid state systems using cold trapped ions that we are pursuing in Mainz.

I will also discuss a new experiment I am currently setting up that aims at performing quantum simulation with a mixture of ultracold atoms and ions. Theoretical analysis shows that fermion-phonon coupling can occur in such systems, leading to solid state phenomena such as the Peierls effect and phonon mediated interactions. The system may also be used to study ion-controlled atomic wavepacket dynamics.

QUANTUM SIMULATION OF A LATTICE SCHWINGER MODEL IN A CHAIN OF TRAPPED IONS

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ABSTRACT

Lattice gauge theories describe fundamental phenomena of high-energy and condensed-matter physics, but are often hard to solve on a classical computer. We discuss how a simple lattice gauge theory, a lattice Schwinger model related to one-dimensional quantum electrodynamics, can be quantum simulated in a linear ion trap.

We show how one can engineer an effectively gauge-invariant dynamics by imposing energetic constraints, provided by strong Ising-like interactions between internal states of the ions. As shown by an analysis of the microscopic model, the proposed scheme allows for the observation in realistic setups of particle-physics phenomena such as spontaneous parity- and charge-symmetry breaking or false-vacuum decay.

The proposal opens a route for analog quantum simulation of high-energy and condensed-matter models where gauge symmetries play a prominent role.

TECHNOLOGIES FOR QUANTUM CONTROL IN TRAPPED ION SYSTEMS

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ABSTRACT

Utilizing unique properties of quantum physics in principle enables computational speeds unmatched by a conventional computer for an important set of problems, fundamentally secure communication over long distances, and our ability to simulate complex quantum systems beyond what classical machines can do. On the other hand, the practical technology to construct a functional, scalable quantum computer, quantum simulator or quantum communication system remains a major challenge. Similar to transistor technology in the early days, we do not have a scalable technology platform on which large numbers of trapped ions can be integrated, nor an architectural framework for assembling a complex functional circuit capable of executing useful algorithms. In this work, I will describe a systems approach to realizing scalable quantum information processing systems utilizing hardware technology available to us today, and the integration effort currently under way.

OBSERVATION OF THE QUANTUM SPEED-LIMIT: LIGHT-CONE-LIKE SPREADING OF QUANTUM CORRELATIONS AND BEYOND.

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ABSTRACT

Finite range interactions between many-body quantum systems are predicted to enforce a quantum speed limit: The maximal speed at which quantum correlations can propagate in such systems. In this talk I will present our (very) recent results on the observation of a 'light-cone' for quantum correlations in a many-body quantum system. Specifically, by using lasers to drive finite range interactions between a string of trapped ionic-qubits, we observe the light-cone-like ejection of entangled quasi-particles after a local quench. Furthermore, we are able to tune the interaction range to regimes where the light-cone picture breaks down.

QUANTUM SIMULATION WITH TRAPPED IONS AT NIST

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ABSTRACT

The NIST ion storage group conducts experiments on quantum simulation with ions based on two different approaches. In a Penning trap, hundreds of ions spontaneously form a triangular 2D lattice that allows for setting up simulations on complex coupled spin systems in a "top-down" fashion. At the same time we are pursuing a "bottom-up" approach where radio-frequency surface electrode trap technology is utilized to construct arbitrary 2D lattices of ions with tailored spin-spin interactions.

The talk will introduce both systems and give updates on the current status of the experiments.

This work has been supported by IARPA, DARPA, ARO, ONR, and the NIST Quantum Information Program.

MICROFABRICATED ION TRAPS FOR QUANTUM SIMULATIONS

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ABSTRACT

Microfabricated ion traps hold great potential for the development of one and two dimensional quantum simulators. The smaller and more complex trap structures and features of microfabricated traps make it possible to perform quantum simulations in 2D arrays, to scale the system to larger numbers of ions and are beneficial if used with microwave entanglement gates.

I will discuss the operation of a microfabricated two-dimensional ion trap array. Ions were trapped in a two-dimensional lattice of ytterbium ions with long ion lifetimes and large secular frequencies. Our device is capable of deterministically introducing lattice defects by trapping multiple ions at a single site which could allow simulation of Bose-Hubbard Physics as well as of systems with spins greater than ½. The ion-ion distance for this device is however too large to be used for quantum simulation. I will discuss how a simple modification to the microchip design would allow for simulation of 2D spin lattices. I will also present our theoretical findings on the optimal two-dimensional ion trap lattice geometry for quantum simulations and the fabrication of such an ion trap design.

Next I will discuss an ion trap geometry designed to achieve a homogenous ion-ion spacing by extending a linear trap geometry to a ring ion trap exhibiting periodic boundary conditions. This electrode arrangement opens up the possibility to study quantum systems such as the homogenous Kibble-Zurek mechanism, Hawking radiation and space time crystals.

Then I will present our progress towards linear and X-junction traps with current-carrying wires intended to produce large static magnetic field gradients. Traps with large adjustable gradients can be used to perform microwave based quantum gates and to perform digital quantum simulations.

Lastly I will discuss the experimental set up of a low vibration (~10nm) cryogenic vacuum system for ion trap operation at 4K. The system features extremely fast turnaround times for efficient testing of new ion trap chip devices and should allow us to reduce the heating rate in our ion traps by several orders of magnitude.

TOPOLOGICAL DEFECT FORMATION AND DYNAMICS IN ION COULOMB CRYSTALS

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ABSTRACT

Structural defects in ion Coulomb crystals (kinks) have been proposed for studies of quantum mechanical effects with solitons and as carriers of quantum information. Defects form when a symmetry breaking phase transition is crossed and the finite speed of information prevents different regions from coordinating the choice of the symmetry broken state. Where such local choices are incompatible, defects will form with densities predicted to follow a power law scaling in the rate of the transition. The importance of this Kibble-Zurek mechanism (KZM) ranges from cosmology to condensed matter. In previous tests in homogeneous systems, defect formation was seen, but weak dependence on the transition rate and limited control of external parameters so far prevented tests of KZM scaling. As recently predicted, in inhomogeneous systems propagation of the critical front enhances the role of causality and steepens scaling of defect density with the transition rate. We use ion Coulomb crystals in a harmonic trap to demonstrate, for the first time, scaling of the number of topological defects with the transition rate – the central prediction of KZM - in a wellcontrolled environment. We will detail on kink dynamics and stability in our system.

Implementing mass defects and electric fields we demonstrate first steps to a controlled kink preparation and manipulation for future studies of nonlinear physics in ion Coulomb crystals.

WEAK DIPOLAR INTERACTIONS IN ION CHAINS

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ABSTRACT

In this talk I will review two experiments in which weak dipolar interactions were measured in a linear chain of trapped ions.

In the first experiment, the magnetic spin-spin interaction between two trapped ions was observed to lead to the entanglement of their collective spin state. The measurement of this ultra-weak (mHz) interaction strength was made possible by restricting their spin evolution to a decoherence-free subspace.

In the second experiment, resonant electric dipole-dipole interactions were measured during photon scattering on an allowed optical dipole transition in chains of up to eight ions. The resonance frequency of the transition was shown to slightly (10's of kHz) shift whenever the separation between ions equalled an integer number of photon wavelength in what is known as collective Lamb shift. This shift is due to emission and re-absorption of virtual photons between different ions in the chain, and is closely related to superadiance.

QUANTUM SIMULATION OF THE HALDANE PHASE USING TRAPPED IONS

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ABSTRACT

A proposal to use trapped ions to simulate spin-one XXZ antiferromagnetic (AFM) chains as an experimental tool to explore the Haldane phase is presented. I will explain how to reach the Haldane phase adiabatically, demonstrate the robustness of the ground states to noise in the magnetic field and Rabi frequencies, and propose a way to detect them using their characterizations: an excitation gap and exponentially decaying correlations, a nonvanishing nonlocal string order and a double degenerate entanglement spectrum. Scaling up to higher dimensions and more frustrated lattices, we obtain richer phase diagrams, and we can reach spin liquid phase, which can be detected by its entanglement entropy which obeys the boundary law.

QUANTUM SIMULATIONS: FROM GROUND TO EXCITED STATES

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ABSTRACT

Trapped-ion quantum simulators are a leading platform for the study of interacting spin systems, such as fully-connected Ising models with transverse and longitudinal fields. Phonon-mediated spin-dependent optical dipole forces act globally on a linear chain of 10-20 trapped Yb-171+ ions to generate the spin-spin couplings, with the form and range of such couplings controlled by laser frequencies and trap voltages. State-dependent fluorescence imaging of the ions onto a camera allows for readout of the individual spin states. Exploiting our precise control over the Ising couplings and external fields, we study a zero-temperature classical spin system in which the physical ground states are classically inaccessible due to the absence of thermal fluctuations. We instead use controlled quantum fluctuations to create the classically forbidden states and gain information about the classical phase transition locations. Two additional experiments move beyond studies of the ground state. In the first, we have developed a spectroscopic technique to resolve the excited state energy levels of our effective many-body system and verify the experimentally applied Hamiltonian. In the second, we perform a global quench and measure the speed at which correlations propagate through the ion chain, testing Lieb-Robinson type bounds in a long-range interacting system.

This work was supported by grants from the U.S. Army Research Office with funding from IARPA, the DARPA OLE program, and the MURI Hybrid Quantum Circuits program; and the NSF Physics Frontier Center at JQI. Co-authors: C. Senko, J. Smith, A. Lee, R. Islam, W. C. Campbell, and C. Monroe.

2D ANALOGUE QUANTUM SIMULATIONS - EXPLOITING IONS (AND ATOMS) IN OPTICAL AND RF-TRAPS

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ABSTRACT

(1) Analogue Quantum simulations in surface radiofrequency traps:

We trapped Mg ions in a linear surface trap (SANDIA-Eurotrap) and are currently implementing our proposal on "dissipation assisted quantum information processing" (collaboration with A. Bermudez and M. Plenio). I will report about the status of the trap's successor, a 2D surface trap (collaboration with NIST,SANDIA and R. Schmied) to explore its capabilities for 2D-quantum simulations (collaboration with D. Porras and A. Bermudez).

In addition, I will summarize our status and our view of the perspectives of the following topics:

(2) We follow the approach, pioneered by a group at MIT in 2009, to exploit the unique control of trapped ions and atoms towards investigating their interaction on the quantum level. However, based on our experimental results on optically trapping an ion, we propose to combine the advantages of ions and atoms (as BEC at ~100nK), trapped in a common optical trap. I want to present and discuss our protocol to reach beyond chemical processes where still many partial waves contribute.

(3) We study experimentally and theoretically structural defects which are formed during the transition from a laser cooled cloud to a Coulomb crystal, consisting of tens of ions in a linear radiofrequency trap. We demonstrate the creation and evidence for trapping of the topological defects (collaboration with H. Landa, A. Retzker and B. Reznik). We will discuss our perspective how to explore and exploit the quantum nature of these objects.

CONTROL OF SINGLE CA+ IONS AND ION COULOMB CRYSTALS IN A PENNING TRAP

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ABSTRACT

We have developed methods to control the conformations of small Ion Coulomb Crystals of Ca+ ions in a Penning Trap. We have also performed spectroscopy revealing motional sidebands for the axial and radial modes of the ion motion. We have used this as a basis for performing ground state cooling of the axial mode and are preparing to extend this to the radial modes and to small ion Coulomb crystals.

HIGH-FIDELITY COMPOSITE PULSE TECHNIQUES FOR QUANTUM COMPUTING AND QUANTUM SIMULATIONS

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ABSTRACT

The technique of composite pulses developed originally in nuclear magnetic resonance is a very versatile tool for quantum state manipulation because it allows one to produce an excitation profile of any desired shape. Motivated by the objective to optimize the manipulation of ion qubits we have developed a pool of new, more powerful composite pulse sequences for single- and multi-qubit quantum gates by using a novel approach based on SU(2) transformations instead of the traditionally used SO(3) rotations on the Bloch sphere. We have designed arbitrarily accurate broadband, narrowband, passband and fractional-pi composite pulses in two-, three- and multilevel systems as well as in ensembles of qubits.

Broadband sequences combine very high fidelity of gate operations with robustness to parameter variations. To this end, we have combined the techniques of composite pulses and chirped adiabatic passage into the new technique of composite adiabatic passage (CAP), in which nonadiabatic losses can be cancelled to any desired order; CAP has been demonstrated very recently in a doped-solid experiment. We have extended this idea further, to composite STIRAP. Moreover, we have constructed universal broadband composite pulses, which compensate variations in any experimental parameter (Rabi frequency, detuning, duration, Stark shift, chirp, pulse shape etc.); these universal pulses have been demonstrated in another doped-solid experiment.

Narrowband and passband composite sequences can reduce dramatically the addressing error in a lattice of closely spaced atoms or ions. In this manner, one can even beat the diffraction limit because only atoms situated in a small spatial region around the centre of the laser beam are excited.

We have used composite pulses to design new, more efficient implementations of highly-conditional quantum gates, such as the Toffoli gate, which require much fewer physical interactions than in the standard circuit model, essentially a single composite pulse. Moreover, we have used composite pulses as a tool to create highly entangled many-particle states, such as Dicke, cluster and NooN states.

TOWARDS MICROWAVE ENTANGLEMENT GENERATION FOR QUANTUM SIMULATION AND COMPUTING

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ABSTRACT

Scalability is a challenging yet key aspect required for large scale quantum computing and simulation using trapped ions. Impressive quantum simulations have been implemented using lasers and a focus now lies on scaling these processes up to a larger number of ions. A promising route relies on the use of stable and easily controllable microwaves [1, 2]. The combination of global microwave fields and static magnetic field gradients are a promising route to scalability by providing ion selectivity as well as the simultaneous entanglement of a large number of ions [1]. Such gate operations are vulnerable to decoherence due to fluctuating magnetic fields [3]. However, the use of microwave-dressed states as qubits protects against this source of noise; with radio-frequency fields being used for qubit manipulation [4]. I will discuss the preparation of such dressed-states using ytterbium ions, and the significant increase in coherence time it produces [5].

The 2nd order Zeeman effect removes the degeneracy of the radio-frequency transitions within the F=1 manifold of the ion's ground state, and I will present our powerful method for manipulating the dressed-state qubit using this property. I will also show that our method allows for the implementation of arbitrary rotations of our dressed-state qubit on the Bloch sphere using only a single rf field [5]. This substantially simplifies the experimental setup for single and multi-qubit gates compared to the original method, reducing the number of rf fields required and removing some of the stringent requirements on the phases of the microwave and rf fields.

I will also present our latest results towards the implementation of a two-qubit entangling gate using dressed-states in conjunction with a static magnetic field gradient. We have constructed an efficient setup based on multiple in-vacuum permanent rare earth magnets which produce a magnetic field gradient of 24 T/m. I will show our most recent results using this setup, including individual addressing of closely spaced ions in frequency space. Furthermore, I will report the coupling between the bare internal and motional states of the ions due to the magnetic field gradient.

The next critical step towards realizing microwave-dressed-state based multi-qubit gate operations is the realization of a coupling between our dressed-states and the motional states. I will report this crucial coupling, achieved by combining our dressed-state and magnetic field gradient setup which shows that while our dressed-qubit is insensitive to magnetic field fluctuations, it remains sensitive to a magnetic field gradient.

The creation of Schrödinger cat states gives a good indication of the level of quantum control possible in a given setup, exhibiting the entanglement of the internal and motional state of the ion. I will report the experimental demonstration of such Schrödinger cat states using microwaves and a static magnetic field gradient.

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ADIABATIC PREPARATION OF SPIN-SPIN HAMILTONIANS FOR LONG-DISTANCE ENTANGLEMENT

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ABSTRACT

We investigate adiabatic quantum simulations in a linear Paul trap taking advantage of various types of spin-spin Hamiltonians. These Hamiltonians with non-commuting interaction terms (e.g., $\sigma^z \sigma^z$ and $\sigma^x \sigma^x$) are generated by creating suitable $\sigma^z \sigma^z$ coupling patterns and through Trotterization using resonant driving of qubit transitions. These Hamiltonians can be varied adiabatically thereby realizing the preparation of the ground states of interesting quantum spin-Hamiltonians.

Of particular interest in these investigations is the quantum simulation of spin models that exhibit long-distance entanglement (LDE) in the ground state. LDE is a global nonclassical effect that can be monitored by the analysis of only two spins, namely the end spins of the chain. It is therefore a sufficiently simple, yet rich phenomenon that could be demonstrated using an ion trap quantum simulator [1].

We have characterized experimentally magnetic gradient induced coupling (MAGIC) between spins in strings of two and three ions and have shown the dependence of this coupling on the secular axial trap frequency [2]. Tailoring of these coupling constants is particularly versatile in ion traps with segmented electrodes. It is shown how static potentials applied to individual electrodes of a micro-structured trap allow for the creation of coupling patterns suitable for creating spin Hamiltonians exhibiting LDE. A Trotter expansion serves for generating the relevant spin-spin interactions in all needed directions and components and shall be implemented by using sequences of RF pulses. These sequences can be made robust against instrumental errors [3].

In addition, we present the design, fabrication, and characterization of a segmented surface ion trap with integrated current carrying structures. The latter produce a spatially varying magnetic field necessary for MAGIC. Trapping of strings of Yb+ ions is demonstrated and the performance of the trap is characterized. Furthermore, a magnetic gradient field is applied, characterized, and used to demonstrate individual addressing in a string of three ions using RF radiation in this surface trap [4].

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Poster Presentations

FROM QUANTUM CONTROL TO QUANTUM SIMULATION WITH TRAPPED IONS

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ABSTRACT

We describe recent insights into the control of quantum mechanical systems in the time domain as filtering, and how this technique may be applied in the context of quantum simulation. In this work, we develop novel sequences of unitary operations that engineer desired effective Hamiltonians, starting only with an arbitrary native inter-particle interaction and single-qubit addressing. The result is a hybrid programmable analog simulator permitting a broad class of interacting spin-lattice models to be generated. We show how determining the relevant hardware "program" of unitary pulses to implement an arbitrary spin Hamiltonian on such a simulator can be formulated as a linear program that runs in polynomial time and scales efficiently in hardware resources. Our analysis extends from circuit model quantum information to adiabatic quantum evolutions, where our approach allows for the creation of non-native ground state solutions to a computation. Recent progress validating the filter-design formalism in quantum control will be presented using trapped 171Yb+ ions.

A PLANAR ELECTRODE ION TRAP WITH INTEGRATED CURRENT CARRYING ELECTRODES FOR ADJUSTABLE MAGNETIC FIELD.

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ABSTRACT

We present a planar electrode ion trap that is designed for the realization of a magnetic gradient induced coupling (MAGIC) scheme. The trap has segmented DC electrodes that allow passing currents through them. These currents can create a highly non-uniform magnetic field in the region of ion trapping, which is needed for MAGIC. Adjusting voltages of DC electrodes and the currents running through them, one can tailor the spin-spin couplings of the trapped ions.

We demonstrate the latest results of experimental characterization of the trap and discuss the future development of the proposed scheme.

LASER COOLED IONS IN LINEAR MULTIPOLE TRAP: A TOOL FOR QUANTUM SIMULATIONS?

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ABSTRACT

Our group investigates the dynamics and equilibrium structures of cold ions in linear traps.

Depending on the trapping potential and for an increasing number of ions, cold ions organize themselves as a single ring, then several rings forming a tube and several tubes inside each other, for a larger number of ions [1]. The single ring structure can be the support of an optical clock [2] and has been proposed to study collective excitations [3]. Due to its periodicity, it could be used as a simulator for a system with periodic limit conditions. Furthermore, the transition from one to two rings [4] is the analogous of the chain to zig-zag transition occurring in linear quadrupole trap. It could thus be a candidate to observe defect formation inside an homogeneous ion crystal.

Larger systems show also interesting features like a melting process appearing in the shell inside the tube for larger temperature than for the outer shells [1]. A single long tube can be seen as a 3D system or a 2D foil closed on itself. The oscillation eigen-modes would then be different. To explore all these features, we have designed and realized an experimental device which is dedicated to the study of large stable ion structures when laser cooled and trapped in a multipole geometry [5]. The trap is made of 8 rods and is loaded from an inline quadrupole trap. Experimental and theoretical issues concerning this multipole trap will be discussed on this poster.

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QUANTUM SIMULATION OF THE HALDANE PHASE USING TRAPPED IONS

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ABSTRACT

A proposal to use trapped ions to simulate spin-one XXZ antiferromagnetic (AFM) chains as an experimental tool to explore the Haldane phase is presented.

We explain how to reach the Haldane phase adiabatically, demonstrate the robustness of the ground states to noise in the magnetic field and Rabi frequencies, and propose a way to detect them using their characterizations: an excitation gap and exponentially decaying correlations, a nonvanishing nonlocal string order and a double degenerate entanglement spectrum.

Scaling up to higher dimensions and more frustrated lattices, we obtain richer phase diagrams, and we can reach spin liquid phase, which can be detected by its entanglement entropy which obeys the boundary law.

INTEGRATED SYSTEM TECHNOLOGIES FOR TRAPPED ION QUANTUM INFORMATION PROCESSING

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ABSTRACT

Scalability is one of the main challenges of trapped ion based quantum computation, mainly limited by the lack of enabling technologies needed to trap, manipulate and process the increasing number of qubits. Microfabricated surface ion traps provide a scalable solution for trapping and shuttling chains of ions, utilizing existing silicon processing technologies. For individual addressing, microelectromechanical systems (MEMS) technology allows one to design movable micromirrors to focus laser beams on individual ions and steer the focal point in two dimensions. This system provides low optical loss across a broad wavelength range and can scale to multiple beams. In order to read the state of the ion chain we image the ion chain with a high numerical aperture lens (0.6 NA) onto a 32-channel PMT with a custom read-out electronics operating near the thermal noise limit of the amplifier.

Using a microfabricated surface trap from Sandia National Laboratories [1] we trap chains of 171Yb+ ions. Using the MEMS mirrors, we perform single qubit gates on individual 171Yb+ ions in a chain with Raman transitions driven by stabilized frequency combs. Using this setup, we sequentially perform single qubit gates on multiple qubits and characterize the gate performance using quantum state tomography.

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CRYOGENIC ION TRAPPING AND GENERAL TECHNOLOGY DEVELOPMENT FOR QUANTUM SIMULATION, COMPUTING AND HYBRID SYSTEMS

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ABSTRACT

We report on progress on a new experiment to operate a variety of surface electrode ion trap chips in a cryogenic environment. Using this setup we aim to study microwave entanglement, anomalous heating, quantum simulations using 2D arrays of trapped ions and technology development towards quantum hybrid systems.

We also present progress on a coplanar waveguide (CPW) resonator with high quality factor integrated into an ion chip. The central DC electrode and the two lateral RF electrodes for ion trapping provide a natural CPW structure for on-chip MW radiation delivery. The ion trap has vertical ion shuttling capability to achieve high and low ion electrode spacing required for laser and MW interactions respectively. Finite element simulation of trap electrodes to obtain critical parameters such as trap depth, potential barrier and low ion height are shown.

We also discuss the experimental set up of a low vibration (~10nm) cryogenic vacuum system for ion trap operation at 4K. The system features extremely fast turnaround times for efficient testing of new ion trap chip devices.

Finally we present progress on an analogue voltage generation system for simultaneous generation of 90 channels with 16 MSPS update rate for fast ion transport. The system is designed using very low noise components and has a combination of digital, active and passive filters and has a maximum range of +/-100V.

RADIO FREQUENCY DRESSED PERIODIC POTENTIALS FOR QUANTUM SIMULATIONS WITH COLD ATOMS

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ABSTRACT

Ultracold atomic gases in periodic potentials are suitable platforms for quantum simulation of physical phenomena ranging from transport problems to high energy physics [1]. In this context, lattices formed by the interference of coherent radiation detuned from optical transitions in atoms, have been used to provide a periodic potential [2]. Although this approach is very controllable and flexible, there is an experimental overhead required for laser stabilization.

In this work we propose the production of periodic lattices based on the dressing of Zeeman shifted atomic states [3], by utilising an array of orthogonal conductors carrying static and radio-frequency currents. We have demonstrated that this system offers a similar flexibility to optical lattices, and propose various mechanisms to completely free the set-up from optical elements. We estimate Hubbard parameters in the regime of deep potential wells [4], which compare favourably with the range accessible with typical optical lattices. The proposed approach can be realized with currently available micro-fabrication techniques.

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QUANTUM SPIN ICE WITH RYDBERG DRESSED ATOMS

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ABSTRACT

We will present a discussion of quantum spin ice, which represents a paradigmatic example on how the physics of frustrated magnets is related to gauge theories.

The goal is to assemble a system of cold Rydberg atoms and to design interactions that realize a toy model of quantum spin ice on a two-dimensional checkerboard lattice. In particular, we exploit the strong angular dependence of Van-der-Waals interactions between high angular momentum Rydberg states. Together with the possibility of designing step-like potentials using ground state atoms weakly dressed by Rydberg states, we can implement Abelian gauge theories in a series of geometries, which could be demonstrated within state of the art experiments.

TRAPPED ION SYSTEM FOR SIMULATIONS OF QUANTUM SPIN MODELS

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ABSTRACT

Cold trapped ions are a powerful platform for exploring many-body spin Hamiltonians [1] and investigating the role of geometric frustration in emergent phenomena. The long coherence times and excellent experimental control over atomic and motional quantum states and interactions afforded by this system have led to promising demonstrations of trapped ion quantum simulators [2, 3]. We are currently working with ion traps which have periodic boundary conditions in order to study highly-frustrated spin models. We describe efforts to study and control ordered systems of charged particles and their formation in an ion trap with radial symmetry.

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HIGH-FIDELITY QIP WITH 43CA+

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ABSTRACT

Quantum simulators and computers offer the tantalising possibility of being able to solve important problems which would be intractable using classical means. So far attempts to build such a device have been limited by the fidelities with which we can control our quantum system. In this poster, we present recent work on high-fidelity QIP using trapped 43Ca+ ions.

43Ca+ offers several particular advantages, which make it an excellent candidate ion for quantum information processing. Its hyperfine structure allows magnetic-field independent clock-states, with a coherence time of order one minute. The presence of a low-lying D-level provides a "shelf"-level for qubit readout, allowing state preparation and measurement fidelity of >99.9%.

We present randomised benchmarking of a single qubit with an error-per-gate of less than one part-per-million and a two-qubit gate based on stimulated Raman transitions with 99.5% fidelity. We also present progress towards a two-qubit gate driven by oscillating microwave field gradients.

SPREAD OF CORRELATIONS IN LONG-RANGE INTERACTING QUANTUM SYSTEMS

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ABSTRACT

The non-equilibrium response of a quantum many-body system defines its fundamental transport properties and how initially localized quantum information spreads. However, for long-range-interacting quantum systems little is known.

We address this issue by analyzing a local quantum quench in the long-range Ising model in a transverse field, where interactions decay as a variable power-law with distance $\propto r^{-\alpha}$, $\alpha>0$. Using complementary numerical and analytical techniques, we identify three dynamical regimes: short-range-like with an emerging light cone for $\alpha>2$; weakly long-range for $1<\alpha<2$ without a clear light cone but with a finite propagation speed of almost all excitations; and fully non-local for $\alpha<1$ with instantaneous transmission of correlations. This last regime breaks generalized Lieb-Robinson bounds and thus locality. Numerical calculation of the entanglement spectrum demonstrates that the usual picture of propagating quasi-particles remains valid, allowing an intuitive interpretation of our findings via divergences of quasi-particle velocities. Our results may be tested in state-of-the-art trapped-ion experiments.

ION STORAGE RING ON A CHIP AND ADVANCED MICROFABRICATED ION TRAPS WITH INTEGRATED CURRENT CARRYING WIRES FOR QUANTUM INFORMATION AND SIMULATION

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ABSTRACT

One way to achieve a scalable homogenous ion-ion spacing is by extending a linear ion trap design to a ring ion trap exhibiting periodic boundary conditions. This electrode arrangement opens up the possibility to study quantum systems such as the homogenous Kibble-Zureck mechanism [1]. We will report the successful demonstration of trapping single Yb ions on a centrally segmented microfabricated ring trap featuring 90 electrodes and a microfabrication technique which allows buried rf and static voltage interconnects [2]. This architecture is capable of storing a string of approximately 1000 ions. We will also report on our investigation into shuttling ions around the ring and the experimental realisation of periodic boundary conditions.

The implementation of static magnetic field gradients can be used to perform microwave based quantum gates and digital quantum simulations [3]. We present a novel microfabrication process suitable to create current carrying wires embedded in a substrate allowing advanced multi-layered ion trap structures to be fabricated on top. The combination of extremely high thermal conductive diamond substrates and copper tracks embedded into the substrate enables the creation of magnetic field gradients of up to 200 T/m.

We present our designs and fabrication results towards linear and X-junction traps. Integrated features include loading and detection slots and traps with spatially and electrically separated rf rails for new shuttling experiments.

When operating ion traps, the voltage is typically limited by surface flashover forming along the surface of a dielectric. By modifying the fabrication process, we have discovered it is possible to more than double the flashover voltage [4]. This allows for larger ion-electrode distances, reducing the effect of anomalous heating.

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ADIABATIC QUANTUM METROLOGY WITH STRONGLY CORRELATED QUANTUM OPTICAL SYSTEMS

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ABSTRACT

We show that the quasi-adiabatic evolution of a system governed by the Dicke Hamiltonian can be described in terms of a self-induced quantum many-body metrological protocol.

This effect relies on the sensitivity of the ground state to a small symmetry-breaking perturbation at the quantum phase transition, that leads to the collapse of the wavefunciton into one of two possible ground states.

The scaling of the final state properties with the number of atoms and with the intensity of the symmetry breaking field, can be interpreted in terms of the precession time of an effective quantum metrological protocol.

We show that our ideas can be tested with spin-phonon interactions in trapped ion setups.

Our work points to a classification of quantum phase transitions in terms of the capability of many-body quantum systems for parameter estimation.

TRAPPED-ION QUANTUM COMPUTING WITHOUT CNOT GATES

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ABSTRACT

We present a novel method for quantum computing with warm trapped ions in a magnetic field gradient. The method builds upon the visionary idea of Mintert &Wunderlich [1] for implementing quantum logic gates with microwave and radiowave radiation.

A series of collective and local operations is applied, where the latter are achieved by standard spin-magnetic resonance and the former occur naturally from free evolution due to the magnetic field gradient. The method is an alternative to the standard computational approach and substitutes the universal gates with carrier pulses applied at specific times.

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A HYBIRD ATOM-ION MICROTRAP

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ABSTRACT

I present the design and development of a new hybrid atom-ion microtrap.

This device can be very useful for studying atom-ion interactions in the 1-dimensional regime and for sympathetic cooling of ions by ultracold atoms. Detailed calculations on an atomic Josephson junction that is controlled by a single trapped ion are also presented.

QUANTUM CONTROL AND DISSIPATION IN MULTI-SPECIES ION CHAINS

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ABSTRACT

I will present recent results of the trapping and control of calcium and beryllium ions in a microfabricated, segmented Paul trap.

The trap is a four-layer design that includes segmented compensation electrodes and that is optimized for implementing quantum control, separation and shuttling of mixed-species ion strings.

The key features of the experimental apparatus include:

- Two high NA imaging systems, consisting of a custom in-vacuum objective for simultaneous diffraction-limited imaging at 313nm and 397nm.

- A >1W 313nm laser system for high-fidelity gate operations in Be+.

- A custom-built FPGA-based control system that uses an embedded processor controlling many distributed programmable DDS systems in a scalable architecture.

I will explain how these new technological elements will enable us to explore mixed-species gates, and perform open system quantum simulations by using one ion species as an artificial environment for the other.

TRAPPED-ION QUANTUM ENGINEERING WITH MICROWAVE NEAR-FIELDS

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ABSTRACT

Common motional states of ions can be used as a "quantum bus" which mediates effective spin-spin interactions between multiple ions. For this purpose, the motional states are coupled to the internal state of a single ion using sideband transitions. In contrast to carrier transitions, sideband transitions couple to the gradient of the driving field. Strong gradients across the size of the motional wavepacket of the ion are commonly produced with laser fields. We present an experimental setup in which we can address sideband transitions using microwave near-fields. Key advantages of using microwave near-fields instead of laser fields are the lack of spontaneous-emission decoherence, low motional-state dependence, potentially superior classical control and integration for scalability [1].

The heart of our experimental apparatus is a micro-fabricated chip containing electrodes for trapping ions and a single, meander-shaped microwave electrode. The near-field produced by this electrode has a local minimum of the magnetic field 30 um above the chip and steep gradients around that minimum as required to address sideband transitions. The magnetic field and the current distribution in the microwave electrode itself as well as the currents induced in other electrodes are efficiently and accurately obtained using full-wave numerical simulations (cf. [2]). We optimised the electrodes' geometry with respect to the ratio of field gradient to residual field at the minimum, which is proportional to the ratio of sideband-to-carrier excitations addressed by the microwave field. We present simulation results, fabrication techniques for building the chip and the experimental hardware required to test the fidelity of the quantum operation that can be performed with the chip.

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DRIVEN GEOMETRIC PHASE GATES WITH TRAPPED IONS

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ABSTRACT

In this poster, we present how the two-qubit entangling gate proposed in [1] can be transformed into a geometric phase gate. The gate relies only on a single red-sideband excitation and a strong microwave driving of the carrier transition. While being technically less demanding than previous schemes [2,3] it can attain errors below the fault-tolerance threshold in the presence of typical sources of noise in ion traps [4]. A thorough study of the gate perfomance in realistic noisy environments is presented. A gate similar to the one presented here has been implemented recently in the group of D. J. Wineland achieving an error of 2.6*10^-2 [5].

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TOPOLOGICAL DEFECT FORMATION AND DYNAMICS IN ION COULOMB CRYSTALS

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ABSTRACT

Structural defects in ion Coulomb crystals (kinks) have been proposed for studies of quantum mechanical effects with solitons and as carriers of quantum information. Defects form when a symmetry breaking phase transition is crossed and the finite speed of information prevents different regions from coordinating the choice of the symmetry broken state. Where such local choices are incompatible, defects will form with densities predicted to follow a power law scaling in the rate of the transition. The importance of this Kibble-Zurek mechanism (KZM) ranges from cosmology to condensed matter. In previous tests in homogeneous systems, defect formation was seen, but weak dependence on the transition rate and limited control of external parameters so far prevented tests of KZM scaling. As recently predicted, in inhomogeneous systems propagation of the critical front enhances the role of causality and steepens scaling of defect density with the transition rate. We use ion Coulomb crystals in a harmonic trap to demonstrate, for the first time, scaling of the number of topological defects with the transition rate – the central prediction of KZM - in a wellcontrolled environment. We will detail on kink dynamics and stability in our system.

Implementing mass defects and electric fields we demonstrate first steps to a controlled kink preparation and manipulation for future studies of nonlinear physics in ion Coulomb crystals.

HIDDEN LONG-RANGE ORDER AND FRUSTRATION IN TRAPPED-ION CRYSTALS.

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ABSTRACT

In the context of Quantum Simulation, we study a particular Hamiltonian over a 1D chain of N S=1/2 systems, that arises naturally in trapped-ion setups, which describes the physics of a Solid State problem known as cooperative Jahn-Teller effect.

In this work we address the fact that this system can exhibit magnetic frustration due to a large range effective coupling between the spins.

NON-EQUILIBRIUM DYNAMICS IN ION COULOMB CRYSTALS

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ABSTRACT

Ion Coulomb crystals are complex self-organized systems with long range non-linear interactions. Their structure can be controlled by precisely varying the trap voltages. For this reason, ion traps constitute excellent experimental systems for studying fundamental phenomena in non-equilibrium statistical mechanics.

Recent experiments [1, 2, 3] studied the process of formation of topological defects following non-equilibrium symmetry breaking phase transitions. In these experiments topological defects (kinks) were created by rapidly transforming a linear chain into a zigzag configuration. The measured scaling of the average number of defects as a function of quench rate is the first accurate measurement of the universal Kibble-Zurek scaling law in the inhomogeneous system.

Structural defects in ion Coulomb crystals are examples of discrete solitons. Discrete solitons are non-linear structures with rich complex dynamics. Ion Coulomb crystals provide an excellent platform for exploring both classical and quantum dynamics of discrete solitons. A number of recent experimental and theoretical works [4, 5] examine the dynamics of discrete solitons in ion traps, in particular focusing on the phonon spectra, Peierls-Nabarro potential, effect of molecular ions and kink-kink interactions.

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QUANTUM PROCESS TOMOGRAPHY OF A MOLMER-SORENSEN ENTANGLEMENT GATE

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ABSTRACT

Here we will show experimental data of quantum process tomography of up to five consecutive Molmer-Sorensen entanglement gates. These gates were driven with a narrow-linewidth (~60 Hz) laser, on optical Sr^+ qubits encoded in states in the $S_{1/2}$ and $D_{5/2}$ manifolds. The gate fidelity of 0.985(10) was shown to be limited by incoherent off-resonance light leading to qubit depolarization.

MICROWAVE CONTROL ELECTRODES FOR SCALABLE, PARALLEL, SINGLE-QUBIT OPERATIONS IN A SURFACE-ELECTRODE ION TRAP

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ABSTRACT

We present a prototype surface ion trap chip [1] with microwave control electrodes for near-field single-qubit control. The chip incorporates two microwave manipulation zones, each with four microwave control electrodes. The electrodes are arranged so as to provide arbitrary frequency, amplitude and polarization control of the microwave field in one trap zone, while nulling the residual microwave field in the neighbouring zone. Our simulations show that crosstalk between trap zones is at the 0.5% level without the use of nulling fields; with nulling, the crosstalk is reduced to 0.01% for realistic microwave amplitude and phase drift.

With the use of multi-level architectures and three-dimensional fabrication techniques, this concept can be scaled up to very large trap arrays. The prototype trap was fabricated in-house using standard photolithography and electroplating techniques and an initial trapping attempt is underway.

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ENTANGLEMENT GENERATION USING DISCRETE SOLITONS IN COULOMB CRYSTALS

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ABSTRACT

Laser cooled and trapped ions can crystallize and feature discrete solitons, that are nonlinear, topologically-protected configurations of the so called Coulomb crystal. Such solitons, as their continuum counterparts, can move within the crystal, while their discreteness leads to the existence of a gap-separated, spatially-localized motional mode of oscillation above the spectrum. We suggest that such unique properties of discrete solitons (kinks), can be used for the purpose of generating entanglement between different sites of the crystal. We study a detailed proposal in the context of state-of-the-art methods and experiments with trapped ions, and find that a discrete soliton can be used to produce EPR and GHZ-type states with high fidelity. The realization of our method requires Doppler cooling of the whole crystal, and sideband cooling of the soliton's localized modes. Since the gap separation of the latter is nearly independent of the crystal's size, the proposed approach could be particularly helpful for producing entanglement and studying system-environment interactions in large, quasi two-dimensional systems.

QUANTUM SIMULATIONS: FROM GROUND TO EXCITED STATES

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ABSTRACT

Trapped-ion quantum simulators are a leading platform for the study of interacting spin systems, such as fully-connected Ising models with transverse and longitudinal fields. Phonon-mediated spin-dependent optical dipole forces act globally on a linear chain of 10-20 trapped Yb-171+ ions to generate the spin-spin couplings, with the form and range of such couplings controlled by laser frequencies and trap voltages. State-dependent fluorescence imaging of the ions onto a camera allows for readout of the individual spin states. Exploiting our precise control over the Ising couplings and external fields, we study a zero-temperature classical spin system in which the physical ground states are classically inaccessible due to the absence of thermal fluctuations. We instead use controlled quantum fluctuations to create the classically forbidden states and gain information about the classical phase transition locations. Two additional experiments move beyond studies of the ground state. In the first, we have developed a spectroscopic technique to resolve the excited state energy levels of our effective many-body system and verify the experimentally applied Hamiltonian. In the second, we perform a global quench and measure the speed at which correlations propagate through the ion chain, testing Lieb-Robinson type bounds in a long-range interacting system.

PRECISE MEASUREMENT OF THE KIBBLE-ZUREK MECHANISM IN ION CRYSTALS

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ABSTRACT

If a system undergoes a second order phase transition into a degenerated ground state, structural defects can be created. This is the case when the transition is crossed fast enough to allow spatially and causally separated regions. The amount of structural defects follows a universal scaling law which was introduced by Kibble and Zurek [1,2]. We have determined the scaling law for defect formation in a crystal consisting of single trapped cold ions, which represents a nearly perfect model system, to study the universal scaling of defects. The possibility for fast changes of the trap control voltages and precise adjustable parameters guarantee an exact observation of the defects at the transition from linear to zig-zag crystal configuration [3]. The experiments were compared with numerical simulations and we were able to confirm the scaling law for the inhomogeneous Kibble-Zurek effect [4,5,6]. Currently we are investigating the effect of the Peierls-Nabarro potential on the confinement of defects. In future we will address defects with laser spectroscopy on the sidebands of the narrow S1/2 to D5/2 transition.

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SINGLE ION HEAT ENGINE

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ABSTRACT

While thermodynamic systems are generally treated by averaging over many body systems, we scale such a system down to the ultimate limit of a single quantum particle. We propose an experimental scheme for a nano heat engine using a single ion as working gas [1]. We use a modified linear Paul trap with tapered geometry (radial electrodes have an angle with respect to the trap axis) to drive the ion in an Otto cycle. Therefore, we couple the ion to engineered reservoirs, realized by laser radiation and tailored electric noise. We demonstrate the experimental feasibility by Monte Carlo simulations. Monte-Carlo simulations with realistic parameters demonstrate its experimental feasibility and its ability to operate at maximum power. Furthermore, we present an experimental scheme to increase the efficiency of the engine beyond the standard Carnot limit by coupling it to a squeezed thermal reservoir [2]. We present a concrete experimental scheme to engineer this interaction and to obtain squeezed states by sudden changes of confining potential. Monte Carlo simulations with realistic trap parameters and laser interaction demonstrate the experimental feasibility of such a scheme with current technology. We further show that this single-ion engine can run at maximum power up to an efficiency which is four times larger than the efficiency obtained with two pure thermal reservoirs and a factor of two above the standard Carnot bound.

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GROUND STATE COOLING IN A PENNING TRAP

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ABSTRACT

We report the sideband cooling of the axial motion of a single ion in a Penning trap to its zero point energy for the first time. We have performed pulsed spectroscopy of the forbidden 729nm S-D transition for a single sideband-cooled Ca+ ion in our trap and made preliminary measurements of the axial heating rate. The Penning trap is the natural choice for study of ion Coulomb crystals of 2 or 3-dimensions, and the ability to ground state cool a single ion is an important step towards carrying out quantum simulation protocols on these types of crystal. We aim to extend this work to the complicated radial motion and to two-ion crystals in the near future. We report sideband cooling of the axial motion in a Penning trap to its zero point energy for the first time.

AN AGILE LASER SYSTEM FOR ENTANGLEMENT AND COHERENT QUBIT MANIPULATIONS IN A MICROFABRICATED ION TRAP

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ABSTRACT

Trapped atomic ions are ideal systems for quantum information processing and quantum metrology.

In our experiment, we realize a qubit based on the electronic states of 88Sr+ ions that are confined in a 3D monolithic microtrap [1,2]. Qubit manipulations are mediated via an optical transition at 674 nm. For advanced experiments, such as teleportation and quantum gates, complex pulse sequences of up to 30 pulses may be required [3].

We have developed a diode laser system at 674 nm that is ideal for generating such pulse sequences with high accuracy [4]. The system is also designed for producing bichromatic pulses for generating entanglement via the scheme of Mølmer and Sørensen [5] (M-S gate).

We show the ability of the system to switch the optical phase, amplitude and frequency with high resolution and high accuracy with a 30 ns rise time limited by the AOM only. The implementation of an automated calibration procedure enables us to use amplitude shaped pulses of arbitrary shape and duration. We compare the performance of experimentally produced square pulses with Blackman pulses using the Fourier transform. We also show the ability to switch between single frequency and bichromatic operation in 30 ns, enabling the combination of arbitrary coherent manipulation and entangling operations.

We are currently combining the laser system with our monolithic 3D ion trap array in order to explore precision spectroscopy and scalable entanglement. Firstly, we are aiming to demonstrate the capabilities of the 674 nm laser system for coherent qubit manipulations on single ions. Secondly, we aim to implement and fully characterise a M-S entangling gate on 2 ions (see e.g. [6]). Finally, we aim to implement and characterise coherent shuttling and splitting operations verified with Ramsey spectroscopy, and 2-ion entanglement. These will be evaluated with respect to possible applications in optical clocks and quantum sensors [7].

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TOWARDS MICROWAVE ENTANGLEMENT GENERATION FOR QUANTUM SIMULATION AND COMPUTING

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ABSTRACT

Scalability is a challenging yet key aspect required for large scale quantum computing and simulation using trapped ions. Impressive quantum simulations have been implemented using lasers and a focus now lies on scaling these processes up to a larger number of ions. A promising route relies on the use of stable and easily controllable microwaves [1, 2]. The combination of global microwave fields and static magnetic field gradients are a promising route to scalability by providing ion selectivity as well as the simultaneous entanglement of a large number of ions [1]. Such gate operations are vulnerable to decoherence due to fluctuating magnetic fields [3]. However, the use of microwave-dressed states as qubits protects against this source of noise; with radio-frequency fields being used for qubit manipulation [4]. We will discuss the preparation of such dressed-states using ytterbium ions, and the significant increase in coherence time it produces [5].

The 2nd order Zeeman effect removes the degeneracy of the radio-frequency transitions within the F=1 manifold of the ion's ground state, and we use this property to demonstrate a powerful method for manipulating the dressed-state qubit. We will also show that our method allows for the implementation of arbitrary rotations of our dressed-state qubit on the Bloch sphere using only a single rf field [5]. This substantially simplifies the experimental setup for single and multi-qubit gates compared to the original method, reducing the number of rf fields required and removing some of the stringent requirements on the phases of the microwave and rf fields.

We will also present our latest results towards the implementation of a two-qubit entangling gate using dressed-states in conjunction with a static magnetic field gradient. We have constructed an efficient setup based on multiple in-vacuum permanent rare earth magnets which produce a magnetic field gradient of 24 T/m. We will show our most recent results using this setup, including individual addressing of closely spaced ions in frequency space. Furthermore, we will report the coupling between the bare internal and motional states of the ions due to the magnetic field gradient.

The next critical step towards realizing microwave-dressed-state based multi-qubit gate operations is the realization of a coupling between our dressed-states and the motional states. We will report this crucial coupling, achieved by combining our dressed-state and magnetic field gradient setup which shows that while our dressed-qubit is insensitive to magnetic field fluctuations, it remains sensitive to a magnetic field gradient.

The creation of Schrödinger cat states gives a good indication of the level of quantum control possible in a given setup, exhibiting the entanglement of the internal and motional state of the ion. We will report the experimental demonstration of such Schrödinger cat states using microwaves and a static magnetic field gradient.

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TWO-DIMENSIONAL ION TRAP LATTICE ON A MICROCHIP AND OPTIMAL LATTICE GEOMETRIES FOR QUANTUM INFORMATION AND SIMULATION

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ABSTRACT

A drawback of current microfabricated ion traps stems from the ions at the rf nil naturally forming a 1-dimensional string, so far, limiting their usefulness for applications that require the formation of arbitrary 2-dimensional (2D) ion lattices, such as analogue quantum simulation [1]. Furthermore, in operating a microfabricated ion surface trap, restrictions on the rf voltage that can be applied due to low flashover voltages exist and prohibit a large trap depth and ion-electrode distance. This limits the achievable ion lifetime and secular frequencies and results in large heating rates of the ion motion.

We will report on the operation of a two-dimensional ion trap lattice integrated on a microchip [2]. For this purpose we first developed a fabrication process that allows extremely large voltages to be applied to microfabricated devices (one or two orders of magnitude higher than in previously fabricated ion traps) which we will also report on. This allowed trapping of a two-dimensional lattice of ytterbium ions with long ion lifetimes and large secular frequencies. Our device is also capable of deterministically introducing lattice defects by trapping multiple ions at a single site which could allow simulation of Bose-Hubbard Physics as well as of systems with spins greater than ½. We will also present our work on rudimentary shuttling of single ions between neighbouring lattice sites.

Furthermore, we will present our theoretical findings on the optimal two-dimensional ion trap lattice geometry for quantum simulation where the focus lies on the optimisation of the ion-ion coupling rate to the decoherence rate [3]. Our optimisation includes maximising of the homogeneity of the coupling rate across the ion lattice. We will also show that the optimum geometry is a function of the ratio between the rf voltage and the drive frequency applied to the lattice.

In addition, we will present devices capable of operating advanced microfabricated ion traps featuring up to 100 electrical connections, high power microwave and current feedthroughs and short turnaround times as well as an in-situ argon ion gun surface cleaning setup for the suppression of anomalous heating.

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A SECOND GENERATION MONOLITHIC 3D ION TRAP ARRAY FOR SCALABLE ENTANGLEMENT

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ABSTRACT

We have demonstrated a microfabricated ion trap device that is etched from a silica-on-silicon wafer [1]. We combine the advantages of a 3D electrode geometry with semiconductor microfabrication techniques to create a trap array in a monolithic chip [2]. The device yields a deep and efficient trapping potential, and 88Sr+ ions have been confined over a wide range of the trap stability parameter, q between 0.17 and 0.7). Radial motional frequencies in excess of 4 MHz, long storage times, and a low heating rate corresponding to om_z*S_e(om_z) = 1.7E-5*V^2/m^2, have been observed for axial motional frequency om_z/2/pi = 750 kHz. Spectroscopy of the 5s 2S1/2 - 4d 2D5/2 optical qubit transition in a single ion shows confinement in the Lamb-Dicke limit.

We have also developed a compact system for containing the microtrap in UHV, which has excellent electronic and optical access [3]. The approach uses a conventional ceramic leadless chip carrier, the conductors of which serve as the vacuum feedthrough. The scheme's electronic connectivity principle is applicable to larger ceramic chip carriers containing many more conductors.

Fabrication of a new batch of ion microtrap chips is underway [4]. This includes 1) trap chips of an improved design with increased segment numbers and a separate loading region, 2) test structures for 2D scalability of trap arrays [5], and 3) test structures for combining with photonic components. A fully masked atomic source will be included in the compact UHV ion trap package [3] to enable degradation-free long term performance of microtraps. Furthermore, we are testing the creation of rf microplasmas for in-situ cleaning of the ion trap electrodes in our compact package for improved heating rates.

The new trap will be used in conjunction with a newly developed laser system with agile control of phase, frequency, amplitude, as well as bichromatic operation [6] to enable arbitrary entangling operations based on the Mølmer-Sørensen gate [7]. With this setup, we will pursue initialisation of a multi-ion string, coherent shuttling and splitting operations verified with Ramsey spectroscopy, and 2-ion entanglement. These will be evaluated with respect to later applications in optical clocks and quantum sensors [8].

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