

Quantum Applications with Trapped Ions

September 16-18, 2013

Topical Group Discussion

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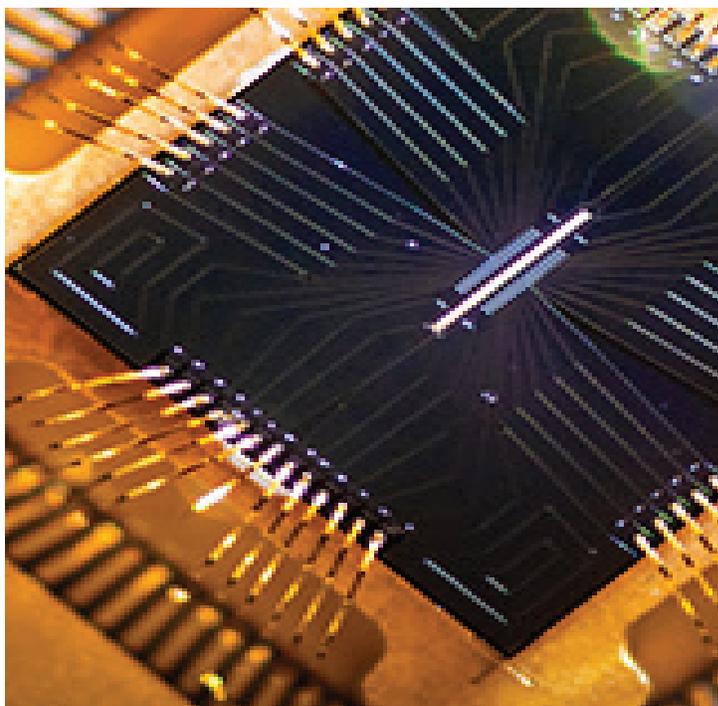
TU Wien

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University of Maryland

“Scalable Trapped Ion Quantum Systems”

September 19-25, 2013



Photograph of a silicon ion trap chip used for applications in quantum information science. Image by Curt Suplee and Emily Edwards, Joint Quantum Institute and University of Maryland. Chip fabricated by Sandia National Laboratories with support from the Intelligence Advanced Research Projects Activity (IARPA).

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Abstract Booklet and Schedule

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Workshop on Quantum Applications with Trapped Ions

Monday, September 16, 2013

Phillips Auditorium

8:15 *Registration, Coffee and Pastries*

8:50 Welcome by Hossein Sadeghpour

8:55 Welcome by the Organizers

Session I: Quantum Control of Trapped Ions, Chair: C. Monroe

9:05 **J. Taylor:** *"Beyond Linear Paul Traps for Scalling Ion Trap Systems"*

09:45 **C. Wunderlich:** *"Elements of Quantum Information Science with Trapped Ions using RF Radiation"*

10:25–10:55 *Coffee Break*

10:55 **H. Häffner:** *"Decoherence and quantum correlations in ion traps"*

11:35 **L. Duan:** *"Space-time crystal and non-equilibrium dynamics with trapped ions"*

12:15–2:00 *Lunch Break*

Session II Molecular Ions and Metrology, Chair: V. Vuletic

02:00 **A. Kuzmich:** *"Optical spectroscopy of triply charged thorium"*

02:40 **B. Odom:** *"Rotational Optical Pumping of Trapped Molecular Ions"*

03:20 **E. Hudson:** *"Sympathetic cooling of molecules with laser-cooled atoms"*

04:00–4:30 *Coffee Break*

04:30 **M. Drewsen:** *"Quantum state preparation and manipulation of single molecular ions"*

05:10 **R. Ozeri:** *"Active Decoherence Suppression methods in Metrology"*

6:00 *Reception*

Tuesday, September 17, 2013

Phillips Auditorium

08:00 *Coffee and Pastries*

Session III: Quantum Computation and Simulation I, Chair: D. Wineland

08:30 **A. Bermudez:** *"Sympathetic dissipative gadgets and quantum transport of correlations in ion crystals"*

09:10 **M. Müller:** *"Open-System Quantum Simulation with Trapped Ions"*

09:50-10:20 *Coffee Break*

10:20 **P. Richerme:** *"Quantum Simulations of Spin Models with Trapped Ions"*

11:00 **J. Bollinger:** *"Quantum simulation with 2-dimensional arrays of hundreds of trapped ions"*

11:40 **A. Wilson:** *"Trapped-Ion quantum information processing experiments at NIST"*

12:30- 2:00 *Lunch Break*

Session IV: Ions and photons, Chair: M. Drewsen

2:00 **J. Eschner:** *"Single-ion – single-photon interfaces"*

2:40 **M. Köhl:** *"Single Ion Coupled to an Optical Fiber Cavity"*

3:20 **V. Vuletic:** *"Suppression of ion transport in an optical lattice"*

4:00-4:30 *Coffee Break*

4:30 **G. Morigi:** *"Quantum dynamics and entanglement of ions in chains close to structural instabilities"*

5:10 **T. Schaetz:** *"Atoms and Ions commonly Trapped by Light – towards Chemistry at the Nano-Kelvin Level"*

5:30 **Poster Session**

Wednesday, September 18, 2013 **Phillips Auditorium**

08:15 *Coffee and Pastries*

Session V: Quantum Computation and Simulation II, Chair: P. Rabl

08:30 **D. Lucas:** *"High-fidelity qubit operations"*

9:10 **A. Retzker:** *"Utilising error correction for quantum sensing"*

9:50-10:20 *Coffee Break*

10:20 **J. Freericks:** *"Eigenstate spectroscopy for spin models in ion trap quantum simulators"*

11:00 **E. Solano:** *"New Perspectives in Quantum Simulations with Trapped Ions"*

11:40 **D. Marcos:** *"Quantum Simulation of Lattice Gauge Theories with Trapped Ions"*

12:30-2:00 *Lunch Break*

Session V: (Continued): Chair: P. Rabl

2:00 **R. Blatt:** *"Open-Systems Quantum Simulations with Trapped Ions"*

2:40 **F. Schmidt-Kaler:** *"From linear to zigzag ion crystals"*

3:30 **Closing of the workshop**

4:00 Tea, Jefferson 250/Physics Department

4:30 **ITAMP/HQOC Quantum Sciences Colloquium – Jefferson 250 Physics Dept.**

D. Wineland: *"Quantum Control of Trapped Atomic Ions"*

Topical Group Discussion on Scalable Trapped Ion Quantum Systems

Thursday, September 19, 2013

Pratt Conference Room

- 9:00 - 10:00 **H. Häffner:** *"Wiring up trapped charged particles---towards an electron based QIP device "*
- 10:00 – 10:30 **C. Monroe:** *"Ion/photon networks and ultrafast entanglement"*
- 2:00 – 3:00 **J. Freericks:** *"Diabatic effects in ion trap based quantum simulation"*
- 3:00 – 3:30 **P. Rabl:** *"Anomalous heating in ion traps: microscopic models."*

Friday, September 20, 2013

Pratt Conference Room

- 9:00 - 10:00 **L. Duan:** *"Ingredients for scalable trapped ion quantum computation"*
- 10:00 – 11:00 **A. Wilson:** *"Scalable Trapped-Ion Quantum Information Processing Experiments at NIST"*
- 2:00 – 3:00 **J. Kim:** *"Quantum Computer In a Box: Where are we, and What's Ahead?"*
- 3:00 – 3:30 **Tony Lee:** *"Quantum simulation of quantum van der Pol oscillators with trapped ions"*

Saturday, September 21, 2013

2:00-4:00

Open for discussions

Tea room

Sunday, September 22, 2013

2:00-4:00 *Open for discussions* **Tea room**

Monday, September 23, 2013**Pratt Conference Room**

9:00 - 10:00 **J. Home:** *"Mixed-species chains, fast transport and trap arrays"*

10:00 - 11:00 **L. Lamata:** *" Quantum Simulations of Fermions and Bosons with Trapped Ions"*

2:00 - 3:00 **F. Schmidt-Kaler /U. Poschinger:** *"From linear to zigzag ion crystals"*

4:00 **ITAMP/HQOC Quantum Sciences Colloquium Phillips Auditorium**
R. Blatt: *"The Quantum way of doing computations"*

Tuesday, September 24, 2013**Pratt Conference**

9:00 - 10:00 **M. Blain:** *" Surface Electrode Ion Trap Device Technology For Quantum Information Science"*

10:00 - 11:00 **J. Casanova:** *" Embedding Quantum Simulators in Trapped Ions"*

2:00 - 3:00 **D. Allcock:** *"Ion trap surface cleaning and microwave-driven gates"*

3:00 - 3:30 Hot Topic

Wednesday, September 25, 2013**Pratt Conference Room**

9:00 - 10:00 TBA

10:00 - 10:30 Hot Topic

2:00 - 4:00 Open for final discussion

Ion Trap Surface Cleaning And Microwave-Driven Gates

D. T. C. Allcock, D.H. Slichter, R. Jördens, U. Warring, Y. Colombe, A.C. Wilson, D.A. Hite, K.S. McKay, D.P. Pappas, D. Leibfried, D.J. Wineland

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We present our current progress towards performing quantum logic gates on trapped-ion qubits at fidelities suitable for fault-tolerant quantum computing. Our two main technical goals are eliminating the so-called anomalous heating of ion motion and improved near field microwave control of hyperfine clock qubits. The effort to reduce the anomalous heating, which limits the fidelity of gates in very small ion traps, is focused on surface treatment methods to remove contaminants from the trap electrodes. We have shown that argon-ion bombardment can reduce the anomalous heating by a factor of 100 [1], and will report on testing other cleaning methods. Our near-field microwave control work will build on previous work on high fidelity single qubit gates [2], single qubit addressing [3] and two-qubit gates [4].

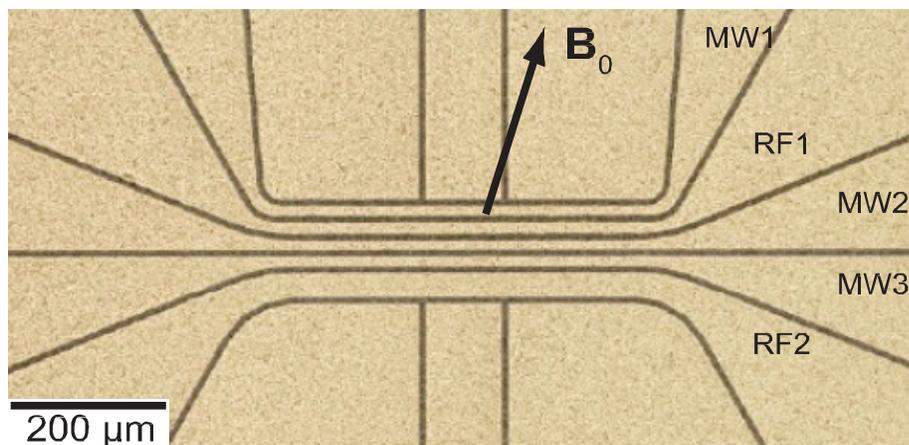


Figure 1: Surface-electrode ion trap for microwave-driven two-qubit gates.

References:

- [1] HITE ET AL. PRL 109, 103001 (2012)
- [2] BROWN ET AL. PRA 84, 030303 (2011)
- [3] WARRING ET AL. ARXIV: 1210.6407 (2012)
- [4] OSPELKAUS ET AL. NATURE 476, 181 (2011)

Sympathetic Dissipative Gadgets And Quantum Transport Of Correlations In Ion Crystals

Alejandro Bermudez

Institute of Fundamental Physics, Spanish Research Council, CSIC

In this talk, I will describe our recent results along two different research lines. In the first part, I will discuss how to use sympathetic laser cooling in mixed species ion crystals as a dissipative gadget for quantum information processing. If time permits, I will try to cover its use for quantum computation (i.e. quantum logic gates robust to heating [1]), dissipative quantum state preparation (i.e. cooling to the ground-state of effective spin Hamiltonians [2]), and quantum simulation (i.e. controlling heat transport along an ion chain [3]). In the second part of the talk, I will discuss how to derive strict bounds (i.e. Lieb-Robinson bounds) on the maximal speed with which spin-spin correlations can build up for general spin-boson lattice models, and how these bounds define an effective "light cone". I will address how this emergence of causality could be tested with trapped ions [4].

References:

- [1] A. BERMUDEZ, T. SCHAEZT, AND M.B. PLENIO, *PHYS. REV. LETT.* 110, 110502 (2013).
- [2] C. CORMICK, A. BERMUDEZ, S.F. HUELGA, AND M.B. PLENIO, *NEW J. PHYS.* 15, 073027 (2013).
- [3] A. BERMUDEZ, M. BRUDERER, AND M.B. PLENIO, *PHYS. REV. LETT.* 11, 040601 (2013).
- [4] J. JUEENEMAN, A. CADARSO, D. PEREZ-GARCIA, A. BERMUDEZ, AND J.J. GARCIA-RIPOLL, *ARXIV: 1307.1992* (2013). TWO-DIMENSIONAL QUANTUM TURBULENCE IN BECS

Surface Electrode Ion Trap Device Technology For Quantum Information Science

Matthew G. Blain, P.L.W. Maunz, A. L. Young,

C. P. Tigges, and D. L. Stick

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The ability to fabricate complex and arbitrary two-dimensional (2-D) trap electrode geometries and electrode arrays is critical to the development of scalable implementations of ion-based quantum systems. To this end, surface electrode ion traps have allowed for the realization of the Kielpinski ion trap CCD (charge coupled device) architecture [1], whereby ions can be moved between different trapping regions optimized for ion loading, and ion entanglement, storage, and initialization/read-out. In particular, the ability to design and fabricate surface electrode trap junctions for the spatial re-ordering of ions [2], precision through-chip holes for ion loading and photon collection/delivery, and arbitrarily shaped trap chips for increased optical access to the ions allows for a highly evolved ion trap chip technology. If engineered appropriately, this trap chip technology may be interfaced to micro-optic device technologies, for example diffractive optical elements (DOEs) or cavity mirrors, to allow for state read-out or coherent information transfer. This “micro-systems” approach to the design and integration of surface electrode ion trap device technology for scaled quantum information science experiments will be discussed in some detail.

**Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.*

- [1] D. KIELPINSKI, ET AL.,
NATURE, 709, 417 (2002).
- [2] D L MOEHRING, ET AL., NEW JOURNAL OF
PHYSICS 13 (2011) 075018.

Quantum Information Processing with Trapped Ca⁺ Ions: error correction and ion photon entanglement

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The Innsbruck quantum information processor operates with strings of trapped Ca⁺ ions. The quantum toolbox available consists of high-fidelity single-qubit and multi-qubit operations. Large entangled states of up to 14 ions were generated with Mølmer-Sørensen entangling gate operations and decoherence of the states was investigated [1]. Phase errors, leading to dephasing of the quantum information, can be actively corrected for by a quantum error correction algorithm [2]. Even a strong measurement on one of the qubits used for encoding can be undone by means of the error correction procedure [3].

In order to scale up an ion trap quantum information processor, a cavity QED setup is used with Ca⁺ ions to generate tunable ion-photon entanglement in an optical cavity [4] and the quantum-state transfer of a single ion to a photon was demonstrated [5], paving the way for larger-scale applications. Using two ions inside a cavity, we generate ion-ion entanglement heralded by the detection of two orthogonally polarized cavity photons [6]. This constitutes a stepping stone for efficient entanglement of remote ions, distributed quantum computing and protocols requiring the controlled coupling of multiple ions to a single cavity.

[1] T. MONZ, ET AL., "14-QUBIT ENTANGLEMENT: CREATION AND COHERENCE", *PHYS. REV. LETT.* 106, 130506 (2011). [2] P. SCHINDLER ET AL., "EXPERIMENTAL REPETITIVE QUANTUM ERROR CORRECTION", *SCIENCE* 332, 1059 (2011).

[3] P. SCHINDLER ET AL., "UNDOING A QUANTUM MEASUREMENT", *PHYS. REV. LETT.* 110, 070403 (2013).

- [4] A. STUTE ET AL., "TUNABLE ION-PHOTON ENTANGLEMENT IN AN OPTICAL CAVITY", NATURE 485, 482 (2012). [5] A. STUTE ET AL., "QUANTUM-STATE TRANSFER FROM AN ION TO A PHOTON", NATURE PHOTONICS 7, 219 (2013).
- [6] B. CASABONE ET AL., "HERALDED ENTANGLEMENT OF TWO IONS IN AN OPTICAL CAVITY", PHYS. REV. LETT. 111, 100505 (2013).

ITAMP/HQOC Quantum Sciences Colloquium

Monday, September 23, 2013, 4:00 pm

Phillips Auditorium

The Quantum Way of Doing Computations

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Since the mid nineties of the 20th century it became apparent that one of the centuries' most important technological inventions, computers in general and many of their applications could possibly be further enormously enhanced by using operations based on quantum. This is timely since the classical roadmaps for the development of computational devices, commonly known as Moore's law, will cease to be applicable within the next decade due to the ever smaller sizes of the electronic components that soon will enter the quantum physics realm.

Computations, whether they happen in our heads or with any computational device, always rely on real physical processes, which are data input, data representation in a memory, data manipulation using algorithms and finally, the data output. Building a quantum computer then requires the implementation of quantum bits (qubits) as storage sites for quantum information, quantum registers and quantum gates for data handling and processing and the development of quantum algorithms.

In this talk, the basic functional principle of a quantum computer will be reviewed and a few technologies for their implementation will be highlighted. In particular, the

quantum way of doing computations will be illustrated by showing how quantum correlations, commonly known as “entanglement” can enhance computational processes. Aside from their use for quantum computers, these quantum technologies open wide perspectives for applications in many technical areas. Examples such as quantum enhanced metrology and quantum simulations will be presented.

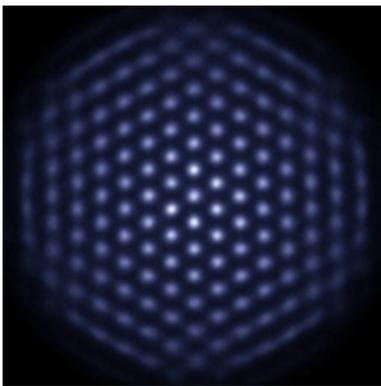
Quantum Simulation With 2-Dimensional Arrays Of Hundreds Of Trapped Ions*

John J. Bollinger, Joseph W. Britton, and Brian C. Sawyer

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Laser cooling large numbers of ions ($>10^8$ [1]) has been demonstrated in Penning traps, which use static electric and magnetic fields for confinement. We investigate whether the large ion crystals [2] that can be readily generated in Penning ion traps can provide useful platforms for quantum information experiments. In particular I will describe our efforts to extend some of the quantum information techniques developed with small linear chains of ions in rf traps [3,4] to two-dimensional triangular arrays of hundreds of ions formed in a Penning trap. Our qubit (or spin) is the 124 GHz electron spin-flip transition in the ground state of Be^+ in the 4.5 Tesla magnetic field of the trap. We control the spins with an effective transverse magnetic field obtained with 124 GHz microwaves [5]. We employ spin-dependent optical dipole forces to measure both the frequency and temperature of the drumhead modes of the triangular arrays [6]. In addition we use spin-dependent optical dipole forces to engineer long-range Ising interactions (both ferromagnetic and anti-ferromagnetic) between the ion qubits [4,7]. We benchmark the interactions through measurements of mean-field spin precession [7]. I will describe the types of Ising interactions we can readily implement and discuss the prospects for simulating the transverse Ising model with hundreds of qubits.

*Supported by the DARPA OLE program and by ARO through the QuISM MURI program.



Fluorescence image of the central portion of a single-plane triangular crystal containing about 300 Be^+ ions stored in a Penning trap. The spacing between neighboring ions is about 20 micrometers. A global rotation has been removed with software

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- [1] F. ANDEREGG, D. H. E. DUBIN, T. M. O'NEIL, AND C. F. DRISCOLL, *PHYS. REV. LETT.* 102, 185001 (2009).
- [2] T. MITCHELL, J. J. BOLLINGER, D. DUBIN, X. HUANG, W. M. ITANO, AND R. BAUGHMAN, *SCIENCE* 282, 1290 (1998).
- [3] R. BLATT, D. WINELAND, *NATURE* 453, 1008 (2008).
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Embedding Quantum Simulators In Trapped Ions

Dr. Jorge Casanova

University of the Basque Country UPV/EHU, Bilbao, Spain

I will introduce the concept of Embedding Quantum Simulators [1], a new paradigm in quantum information allowing the physical implementation of unphysical operations, as is the case of complex conjugation [2] or Galilean Boosts [3] in a quantum controllable setup, as is the case of trapped ions. Moreover, I will show how embedding quantum simulators can be used for the efficient computation of quantities as entanglement monotones or eigenenergies of complex Hamiltonians.

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Quantum State Preparation And Manipulation Of Single Molecular Ions

Michael Drewsen

QUANTOP

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For more than a decade, the translational degrees of freedom of trapped ensembles of molecular ions have efficiently been cooled to the few millikelvin through Coulomb interaction with simultaneously trapped and laser Doppler cooled atomic ions [1]. More recently methods to produce rovibrational cold ensembles of translationally cold molecular ions have as well been demonstrated [2,3]. In the talk, I will present our recent progresses towards generating a single molecular ion in its absolute ground state with respect to both its rovibrational motion and its motion in the external trapping potential [4-6], and discuss a few planned fs laser induced rotational state manipulation experiments.

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Space-Time crystal and dynamical quantum phase transitions with trapped ions

Luming Duan

University of Michigan

In this talk, I will explain the controversial concept of time crystal and its proposed implementation with trapped ions. I will then show how to observe dynamical phase transitions and peculiar perthermalization phenomenon in trapped ions through laser manipulation of its spin dynamics.

Ingredients for scalable trapped ion quantum computation

Luming Duan

University of Michigan

In this talk, first I will review several ideas to make the trapped ion quantum computation more scalable, including using the transverse phonon modes for quantum gates, the optimized gates without phonon sideband addressing, the non-harmonic ion trap, individual addressing through spatial refocusing, and correction of the detection errors. Then I will show an application of this setup for a scalable realization of the bosonic sampling algorithm, a discrete qudit algorithm proven to be intractable by any classical computers.

Single-Ion – Single-Photon Interfaces

Jürgen Eschner

Experimentalphysik, Universität des Saarlandes,

Campus E2 6, 66123 Saarbrücken, Germany

<http://www.uni-saarland.de/lehrstuhl/eschner>

Quantum networks require the conversion between photonic and atomic quantum states. We demonstrate various implementations of controlled interaction between single trapped ions and single photons.

We generate single photons with controlled temporal, spectral, and polarization properties through a laser-driven spontaneous Raman process [1-3]. The photons have between ~ 15 ns and ~ 1 μ s duration and are near-Fourier-limited [1,2]. In one experiment, single photons from one ion are transmitted over ~ 1 m distance to a second single ion, where they are absorbed; individual absorption events are detected employing a quantum-jump heralding scheme [3]. In another experiment, Raman photons are generated from an ion which is initially prepared in a coherent superposition of Zeeman sub-levels. This is a prerequisite for heralded quantum storage of photon polarisation states [4].

We also demonstrate heralded absorption by a single trapped ion of single photons from a Spontaneous Parametric Down-Conversion (SPDC) source; the entanglement of the SPDC photon pair is manifested in the polarisation correlation between photon absorption and detection of the heralding partner [5,6].

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Eigenstate Spectroscopy For Spin Models In Ion Trap Quantum Simulators

James Freericks

Georgetown University

Limitations from decoherence times and spontaneous emission rates often restrict ion-trap-based quantum simulators from performing adiabatic state evolution due to the limitations on experimental run times. In this presentation, I will discuss recent theoretical work we have been engaged in to use the excitations created by a diabatic evolution as a means to measure the excitation energies of the simulated spin model by tracking the temporal evolution of probabilities for the time-independent Hamiltonian after a diabatic evolution from a prepared initial state. In general, one needs to use signal processing techniques like compressive sensing to extract meaningful results from a small data set for realistic experimental protocols. If available, I will compare theoretical results with preliminary data from linear Paul traps with small numbers of ions. Finally, we will compare and discuss alternative means for eigenstate spectroscopy such as modulating fields or detunings as functions of time.

This work is in collaboration with Bryce Yoshimura and Wes Campbell. It is supported by DARPA, NSF, the McDevitt bequest at Georgetown, and the ARCS Foundation.

Decoherence And Quantum Correlations In Ion Traps

Hartmut Häffner

University of California, Berkeley

In the first part of my presentation, I will discuss heating rate measurements of a microfabricated surface trap complemented with basic surface science studies. The goal of these measurements are to learn more about the source of the so-called anomalous heating. We monitor the elemental surface composition of the Cu-Al alloy trap with an Auger spectrometer. After bake-out, we find a strong Carbon and Oxygen contamination and heating rates of 200 quanta/s at 1 MHz trap frequency. After removing most of the Carbon and Oxygen, the heating rates drop to 4 quanta/s. Interestingly, we still measure the decreased heating rate even after the surface oxidized from the background gas throughout a 40-day waiting time in UHV.

In the second part of my presentation, I will discuss simple experiments highlighting the limitations of the density-matrix approach. The standard master equation assumes that the open quantum system under investigation does not share quantum correlations with its environment. In our experiment, we create quantum correlations of the electronic state of a single trapped ion with the motional degree-of-freedom of the ion. By comparing the time evolution of the electronic state of the open quantum system (electronic state of the ion) with and without sharing quantum correlations with the environment, we experimentally demonstrate the importance that such quantum correlations can invalidate the standard master equation approach. We use this method to verify the presence of system-environment quantum correlations by only accessing the open system.

Sympathetic Cooling Of Molecules With Laser-Cooled Atoms

Eric R. Hudson

UCLA

Cooling molecules through collisions with laser-cooled atoms is an attractive route to ultracold, ground state molecules. The technique is simple, applicable to a wide class of molecules, and does not require molecule specific laser systems. Particularly suited to this technique are charged molecules, which can be trapped indefinitely, even at room temperature, and undergo strong, short-ranged collisions with ultracold atoms.

In this talk, I will focus on recent efforts to use the combination of a magneto-optical trap (MOT) and an ion trap, dubbed the MOTion trap, to produce cold, ground state diatomic charged molecules. The low-energy internal structure of these diatomic molecules, *e.g.* the electric dipole moment and vibrational, rotational, and Ω -doublet levels, presents a host of opportunities for advances in quantum simulation, precision measurement, cold chemistry, and quantum information. Excitingly, recent proof-of-principle experiments have demonstrated that the MOTion trap is extremely efficient at cooling the vibrational motion of molecular ions.

Single Ion Coupled to an Optical Fiber Cavity

Matthias Steiner¹, Hendrik M. Meyer¹, Jakob Reichel²,
and Michael Köhl^{1,3}

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³ *Physikalisches Institut, University of Bonn, Wegelerstrasse 8, 53115 Bonn, Germany*

We present the realization of a combined trapped-ion and optical cavity system, in which a single Yb ion is confined by a micron-scale ion trap inside a 230 μm -long optical fiber cavity. We characterize the spatial ion-cavity coupling and measure the ion-cavity coupling strength using a cavity-stimulated Λ -transition. Owing to the small mode volume of the fiber resonator, the coherent coupling strength between the ion and a single photon exceeds the natural decay rate of the dipole moment. We demonstrate the generation of single photons from the coupled ion-cavity system as well as observing correlations between the spin-state of the ion and the polarization state of the photons. This system can be integrated into ion-photon quantum networks and is a step towards cavity quantum electrodynamics based quantum information processing with trapped ions.

Optical Spectroscopy Of Triply Charged Thorium

Alex Kuzmich

Georgia Tech

Atomic nuclei usually possess excitation energies in the keV to MeV range. A notable exception is the ^{229}Th nucleus where the energy splitting of the ground state doublet is less than 10 eV. This fortuitous coincidence offers prospects for a next-generation clock and for a test of temporal variation of fundamental constants at an unprecedented level of precision. The monovalent character of the Th^{3+} ion is favorable for the isomer level search based on the electron bridge process. Optical spectroscopy of laser cooled and crystallized triply charged ^{229}Th in a linear Paul trap will be presented. The nuclear excitation from the ground-electronic level of a single trapped, cold $^{229}\text{Th}^{3+}$ ion is expected to be an ideal system for metrological applications.

Quantum Simulations of Fermions and Bosons with Trapped Ions

Lucas Lamata

University of the Basque Country UPV/EHU, Bilbao, Spain

I will discuss different proposals for quantum simulations of fermions and bosons in trapped ions. I will describe a scalable approach towards the simulation of quantum field theories in trapped ions [1], the realization of interacting fermion lattice models in an efficient manner [2], and the quantum simulation of the Holstein model [3]. I will show that trapped ions are a versatile and efficient tool for the implementation of quantum simulations of interacting fermionic and bosonic models.

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Quantum Simulation Of Quantum Van Der Pol Oscillators With Trapped Ions

Tony Lee

ITAMP

Van der Pol oscillators are prototypical self-sustaining oscillators which have been used to model nonlinear processes in biological and other classical processes. In this work, we investigate how quantum fluctuations affect phase-locking in one or many van der Pol oscillators. We find that phase-locking is much more robust in the quantum model than in the equivalent classical model. Trapped-ion experiments are ideally suited to simulate van der Pol oscillators in the quantum regime via sideband heating and cooling of motional modes. We provide realistic experimental parameters for Yb-171+ achievable with current technology.

High-Fidelity Qubit Operations

David Lucas

Clarendon Laboratory, Oxford University, U.K.

We report on recent work implementing high-fidelity qubit operations in calcium ions.

We use an intermediate-field “atomic clock” qubit in calcium-43 to implement all single-qubit operations (state preparation, readout, and single-qubit gates) with fidelities above 99.95%, and measure a coherence time of 50s. These results are achieved in a room-temperature 2D surface trap (pictured below), using near-field microwaves for coherent manipulation.

In separate experiments in a macroscopic 3D trap, we implement laser-driven two-qubit gates in both calcium-40 and calcium-43 ground-state qubits with fidelities of approximately 98%.

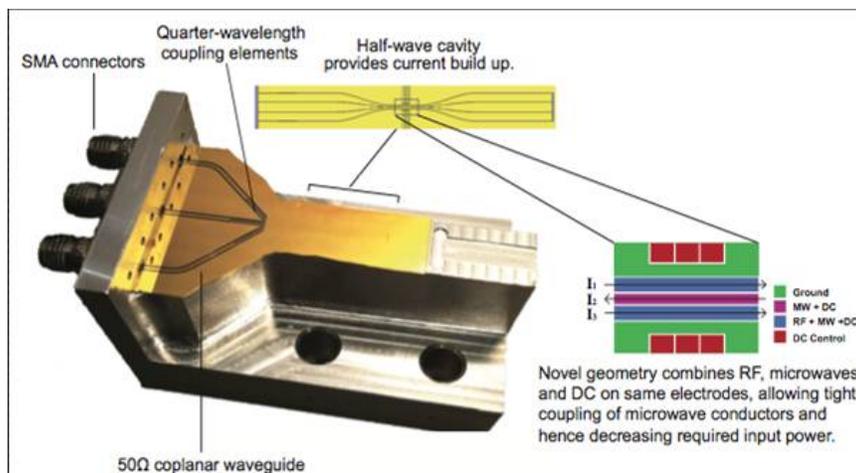


Figure: Oxford surface trap for near-field microwave (3.2GHz) manipulation of calcium-43 ground-state hyperfine qubits.

Quantum Simulation Of Lattice Gauge Theories With Trapped Ions

David Marcos

University of Innsbruck

We discuss how a lattice Schwinger model can be realized in a linear ion trap, allowing a detailed study of the physics of Abelian lattice gauge theories related to one-dimensional quantum electrodynamics. Relying on the rich quantum-simulation toolbox available in state-of-the-art trapped-ion experiments, we show how one can engineer an effectively gauge-invariant dynamics by imposing energetic constraints, provided by strong Ising-like interactions. Applying exact diagonalization to ground-state and time-dependent properties, we study the underlying microscopic model, and discuss undesired interaction terms and other imperfections. As our analysis shows, the proposed scheme allows for the observation in realistic setups of spontaneous parity- and charge-symmetry breaking, as well as false-vacuum decay. Besides an implementation aimed at larger ion chains, we also discuss a minimal setting, consisting of only four ions in a simpler experimental setup, which enables to probe basic physical phenomena related to the full many-body problem. The proposal opens a new route for analog quantum simulation of high-energy and condensed-matter models where gauge symmetries play a prominent role.

Quantum dynamics and entanglement of ions in chains close to structural instabilities

Giovanna Morigi

Saarland University

Quenches in an ion chain can create coherent super positions of motional states across the linear-zigzag structural transition. The procedure has been described in Baltrusch et al. [Phys. Rev. A 84 063821 (2011)] and makes use of spin-dependent forces, so that a coherent superposition of the electronic states of one ion evolves into an entangled state between the chain's internal and external degrees of freedom. The properties of the crystalline state so generated are theoretically studied by means of Ramsey interferometry on one ion of the chain. An analytical expression for the visibility of the interferometric measurement is obtained for a chain of an arbitrary number of ions and as a function of the time elapsed after the quench. Sufficiently close to the linear-zigzag instability the visibility decays very fast, but exhibits revivals at the period of oscillation of the mode that drives the structural instability. These revivals have a periodicity that is independent of the crystal size, and they signal the creation of entanglement by the quantum quench.

We then theoretically show how two impurity defects in a crystalline structure can be entangled through coupling with the crystal. We demonstrate this with a harmonic chain of trapped ions in which two ions of a different species are embedded. After a quench, entanglement is found for sufficiently cold chains and for a certain class of initial, separable states of the defects. It results from the interplay between localized modes which involve the defects and the interposed ions, it is independent of the chain size, and it decays slowly with the distance between the impurities. We show that this entanglement can be revealed by means of spectroscopic measurements and it increases when the ion interparticle spacing varies along the chain, as it is the case in a linear Paul trap.

Open-System Quantum Simulation with Trapped Ions

Markus Müller

Departamento de Física Teórica I, Facultad de Ciencias Físicas,

Universidad Complutense de Madrid, Spain

A universal quantum simulator is a controllable device, which allows one to reproduce efficiently the dynamics of any other quantum system with short-range interactions. Such time evolution can refer to coherent Hamiltonian dynamics of closed quantum systems, as well as dissipative open-system dynamics. In our talk we introduce schemes for digital quantum simulation with trapped ions. We show how to use combinations of coherent quantum gates with optical pumping of ancillary qubits for the engineering of coherent and dissipative multi-particle Kraus maps. These can be harnessed for the simulation of complex Hamiltonians involving n-body interactions such as Kitaev's toric code, as well as for the dissipative preparation and stabilization of entangled states and quantum phases. Furthermore, we show how the competition of coherent and dissipative dynamical maps can lead to novel non-equilibrium manybody dynamics with associated dynamical phase transitions with no immediate counterpart in equilibrium condensed matter systems. We report on a series of recent experiments with trapped ions, where the concepts of digital and open-system quantum simulation have been demonstrated and the hallmark signatures of open-system non-equilibrium many-body physics have been observed, using up to six qubits. Finally, we discuss an error detection and reduction toolbox based on open- and closed-loop feedback schemes, which has been recently developed and implemented as a first step in the direction of faithful quantum simulation of larger systems.

Rotational Optical Pumping of Trapped Molecular Ions

Brian Odom

Northwestern University

Control of the rotational state remains a significant challenge for many trapped molecular ion experiments. Improved ability to control the rotational state on fast timescales would open up new possibilities for precision spectroscopy and for quantum information processing with molecules. Primarily because of the diagonal Franck-Condon factors in A-X or B-X transitions, our group at Northwestern University has chosen to work with AlH^+ and SiO^+ molecular ions. Optical pumping into the ground state using a pulse-shaped femtosecond laser is expected to achieve high efficiency state control in microsecond timescales. I will describe our experimental progress on rotational cooling of these two molecular ion species.

Active Decoherence Suppression Methods in Metrology

Roe Ozeri

Weizmann Institute

Decoherence limits to the accuracy of quantum sensors. In quantum computing, methods were developed to suppress decoherence. Dynamic decoupling, the encoding of information in decoherence-free-subspaces, and quantum error-correction, have all been implemented in quantum computing experiments and enabled the prolongation of coherence times. Here I will describe how we use active decoherence suppression in trapped ion qubits in order to improve the accuracy of precision measurements. We have shown how dynamic modulation techniques, analogues to the lock-in amplifier methods can be used to improve the sensitivity of phase evolution under Zeeman and Stark shifts. We used a decoherence free subspace to measure the magnetic interaction between two electronic spins of ions that were separated by more than 2 microns. Lastly I will discuss the prospects of using quantum error-correction techniques to improve on precision measurements.

Utilising Error Correction for Quantum Sensing

Alex Retzker

University of Jerusalem

Dynamical decoupling has proven very useful for improving the signal to noise ratio of quantum sensing protocols. However, dynamical decoupling is limited in its efficiency, due to energy limitations or noise in the controls. In this talk I will present a few schemes that overcome these limitations using error correction.

Quantum Simulations of Spin Models with Trapped Ions

Phillip Richerme

JQI

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. Additionally, we have developed a spectroscopic technique to resolve the excited state energy levels of our effective many-body system and to coherently engineer highly entangled states. We expect such verification of the experimentally applied Hamiltonian to be crucial as we extend the system to 30+ spins, where classical computations of many-body dynamics become intractable.

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.

Atoms and Ions Commonly Trapped by Light – Towards Chemistry at the Nano-Kelvin Level

Tobias Schaetz

University of Freiburg ,Germany

1. 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 ~ 100 nK), 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.

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

2. Analogue Quantum simulations in surface radiofrequency traps:

We trapped Mg ions in a linear surface trap (SANDIA-Eurotrap) and are currently realizing therein 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).

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.

From Linear To Zigzag Ion Crystals

Ferdinand Schmidt-Kaler

University Mainz

Ion crystals are among the most controlled quantum systems. The crystal structure is controlled with high precision using the dynamic and the static Paul potentials. As an alternative to quantum computation which small linear crystals, shuttled in micro trap arrays, as pioneered by Wineland et al. [Science 325, 1227 (2009)] we aim for planar crystal structures, and investigate this structural transition [PRL 109, 263003 (2012)] also under non-equilibrium conditions [Nat. Comm. 4, 2290 (2013)]. Interactions for quantum magnetic simulations are mediated using laser interactions. State-dependent forces are generated with non-resonant Raman beams [NJP 14, 093042 (2012), PRL 107, 207209 (2011), PRL 108, 235701 (2012)]. A novel approach is the use of specific properties of Rydberg excitations for trapped ion crystals, we prepare a cold 40-Ca⁺ ion crystal, excite the S_{1/2} - D_{5/2} transition near 729nm and apply radiation near 123nm for Rydberg excitation. We report the investigation of mixed crystals of single and doubly ionized Ca, for mode design and structural configuration [arxiv 1306.1109] along the proposals [PRL 108, 023003 (2012), PRA 87, 052304 (2013)].

New Perspectives in Quantum Simulations with Trapped Ions

Enrique Solano

University of the Basque Country UPV/EHU & IKERBASQUE, Bilbao, Spain

I will present novel perspectives for trapped-ion quantum simulators. In particular, I will present two research lines: i) the efficient analog-digital quantum simulation of interacting fermionic and bosonic models, ii) the concept of embedding quantum simulators. Finally, I will argue that both avenues represent a significant step forward in the general framework of quantum simulations in trapped-ion technologies.

Beyond Linear Paul Traps For Scaling Ion Trap Systems

J. M. Taylor

JQI/NIST

The great success of the linear Paul trap as a testbed for ion-based computation now suffers from the challenge of scaling. While many efforts for integrating scaling via shuttling, near-field dipolar coupling, and ion-optical photon entanglement are being pursued, here we examine some alternative approaches. One approach is the Penning trap system, where large ion-numbers become accessible, and I will review efforts and progress for building quantum simulators and quantum computers using such traps. The other approach is coupling ions directly to superconducting circuits, to take best advantage of the rapid advances in circuit QED to enable long-range ion-ion coupling mediated by superconducting buses. A crucial feature of this coupling is an efficient, parametric conversion of natural ion motional frequencies of a few to 10s of MHz to natural circuit QED frequencies of several GHz. We show how this can be achieved at liquid Helium temperatures using either mechanical or Josephson-junction-based parametric coupling. With this building block, all the well-known quantum information protocols linking ion internal and motional states can be converted to protocols between circuit photons and ion internal states. Our results enable quantum interfaces between solid state qubits, atomic qubits, and light, and lay the groundwork for a direct quantum connection between electrical and atomic metrology standards.

Suppression of Ion Transport in an Optical Lattice

Alexei Bylinskii, Dorian Gangloff, Leon Karpa, Marko Cetina,
and **Vladan Vuletic**

MIT, Department of Physics and Research Laboratory of Electronics

We report the localization of an ion by a one-dimensional optical lattice in the presence of an applied external force. The ion is confined radially by a radiofrequency trap and axially by a combined electrostatic and optical-lattice potential. Using a resolved Raman sideband technique, one or several ions are cooled to a mean vibrational number $\langle n \rangle = 0.1 \pm 0.1$ along the optical lattice. We measure the average position of a periodically driven ion with a resolution down to $\lambda/40$, and demonstrate localization to a single lattice site for up to 10 milliseconds. This opens new possibilities for studying many-body systems with long-range interactions in periodic potentials, as well as fundamental models of friction.

Trapped-Ion Quantum Information Processing Experiments at NIST*

Andrew C. Wilson

National Institute of Standards & Technology

325 Broadway, Boulder, CO 80305, U.S.A.

We present implementations of newly-proposed, robust, schemes for generation of entanglement [1] and performing two-qubit gate operations [2] with trapped ions. A method of combining unitary processes with engineered dissipation is used to deterministically produce and stabilize an approximate Bell state of two trapped-ion qubits, independent of their initial state [3]. This is in contrast to the more common approach of using quantum gates to generate entanglement, and a step towards dissipative quantum computation [4]. We also describe implementations of a new dressed-state phase gate [5]. Like the Mølmer Sørensen gate [6], the new scheme is suitable for magnetic field-insensitive states and is robust against thermal excitations. However, it includes dynamical decoupling from qubit-dephasing errors and is simpler to implement in the laboratory. As part of our efforts to realize a device for quantum simulation based on a 2-D array of individually confined ions [7], we use the dressed-state phase gate to produce entanglement between two ions confined in separate trapping zones of a micro-fabricated surface-electrode trap.

* Supported by IARPA through ARO (Grant No. DNI-11523A1), ONR, and the NIST Quantum Information Program, the European Union's Seventh Framework Program through SIQS (grant no. 600645) and ERC grant QIOS (Grant no. 306576).

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ITAMP/HQOC Quantum Sciences Colloquium

Wednesday, September 18, 2013, 4:30 pm

Jefferson 250, Physics Department

(Tea at 4 pm)

Quantum Control of Trapped Atomic Ions

D. J. Wineland

NIST, Boulder, CO

Precise control of quantum systems currently occupies many labs throughout the world, with recent interest focusing on quantum information. This talk will focus on quantum-state manipulation in the context of trapped ions, one example of similar work that is being carried out with many other AMO and condensed matter systems.

Elements of Quantum Information Science with Trapped Ions using RF Radiation

Christof Wunderlich

Siegen University, Germany

With trapped ions unsurpassed control of the quantum degrees of freedom of individual particles has been achieved. When contemplating the scalability of trapped ions for quantum information science one notes that the use of laser light for *coherent manipulation* gives rise to fundamental and technical issues. Recently, laser-less addressing of ions in a magnetic field gradient and Magnetic Gradient Induced Coupling (MAGIC) between ion spins and their motion using radio-frequency (RF) radiation has been demonstrated.

Here, we report on recent experimental progress using trapped ion spin “molecules” that exhibit spin-spin interactions due to MAGIC. Resonances of individual spins are well separated and are addressed with high fidelity. Quantum CNOT gates are carried out using RF radiation. In addition, we characterize experimentally the spin-spin-coupling in strings of two and three ions and prove the dependence of this coupling on the trap frequency which can be used to create tailored coupling patterns relevant, for instance, for quantum simulations.

Tailoring of 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 together with suitable RF pulses allow for creating various spin-spin coupling Hamiltonians.

Dynamical decoupling (DD) is a widely used technique, originally developed in the framework of nuclear magnetic resonance, to protect the coherence of quantum systems against a detrimental environment. Decoherence due to fluctuating magnetic fields can be strongly suppressed using RF-dressed states and coherence times have been prolonged by about three orders of magnitude.

Another approach to coherence protection is pulsed DD. We investigated different pulse sequences with respect to their capability to suppress decoherence while still being robust against pulse imperfections in an ion trap experiment. Results obtained with $^{171}\text{Yb}^+$ 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.

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 magnetic gradient induced coupling. Trapping of strings of Yb^+ ions is demonstrated and the performance of the trap is characterized. In addition, we apply and characterize a magnetic gradient and demonstrate individual addressing in a string of three ions using RF radiation in this surface trap.