Q 24: Quantum Information (Quantum Computing)

Time: Wednesday 11:00–13:00 Location: e001

Group Report Q 24.1 Wed 11:00 e001

Rydberg trapped ions, a novel platform for quantum computing, quantum simulation and sensing — •Arezoo Mokhberi[1], Jonas Vogel[1], Justas Andrijauskas[1,2], Ron Müller[1], and Ferdinand Schmidt-Kaler[1,2] — [1]QUANTUM, Institut für Physik, Universität Mainz, D-55128 Mainz, Germany — [2]Helmholtz-Institut Mainz, D-55128 Mainz, Germany

Cold and controlled atoms and ions are currently of great interest for applications in quantum information processing, simulation and sensing. Excitation of trapped ions to their Rydberg states offers a unique opportunity for combining advantages of precisely controllable trapped-ion qubits with long-range and tunable Rydberg interactions [1,2]. As an exciting application, we proposed a method for fast entangling operations using Rydberg trapped ions which are shuttled in a Paul trap [3]. The state-dependent kick is resulted from impulsive electric pulses [4] acting on ions in Rydberg states with huge polarizability, and it gives rise to a geometric phase that is controlled using experimental parameters [3]. We also discuss our new experimental setup in Mainz which is designed for coherent manipulation of Rydeberg states of $^{40}Ca^{+}$ ions using a two-photon process, and present our results for Rydberg spectroscopy of S and D series.

[1] Feldker et al., *Phys. Rev. Lett.* **115**, 173001(2015)
[2] Higgins et al., *Phys. Rev. Lett.* **119**, 220501 (2017)
[3] Vogel et al., *Phys. Rev. Lett.* **123**, 153603 (2019)
[4] Walther et al., *Phys. Rev. Lett.* **109**, 080501 (2012)

Q 24.2 Wed 11:30 e001

Sub-microsecond entangling gate between trapped ions via Rydberg interaction — •Chi Zhang[1], Fabian Pokorny[1], Weibin Li[2], Gerard Higgins[1], Igor Lesanovsky[2,3], and Chi Zhang[1] — [1]Department of Physics, Stockholm University, 10691 Stockholm, Sweden — [2]School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, United Kingdom — [3]Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

Trapped Rydberg ions [1] are a novel approach for quantum information processing. By combining the high degree of control of trapped ions with the strong dipolar interaction of Rydberg atoms, fast entanglement gates may be realized in large ion crystals.

In our experiment, we excite trapped 88Sr+ ions to Rydberg states [2,3]. We have observed strong interaction between microwave-dressed Rydberg ions as a Rydberg blockade [4]. Recently, we have realized a controlled phase gate in a two ion crystal within only 700ns and entangled the ions with more than 70% fidelity [4]. This fast gate does not rely on ion motion, so it could also be applied in longer ion crystals. These are fundamental steps towards a trapped Rydberg ion quantum computer or simulator.

[1] M. Müller, et al., New J. Phys. 10, 093009 (2008).
[2] G. Higgins, et al., Phys. Rev. X 7, 021038 (2017).
[3] G. Higgins, et al., Phys. Rev. Lett. 119, 220501 (2017).
[4] C.Z. et al., arXiv:1908.11284 (2019).

Q 24.3 Wed 11:45 e001

Benchmarking high-fidelity mixed-species entangling gates — •Vera Schäfer, Amy Hughes, Keshav Thirumalai, David Nadlinger, Christopher Ballance, and David Lucas — Department of Physics, University of Oxford, UK

Simultaneous trapping of two different elements of ion allows the manipulation of one without corruption of the electronic state of the other. An entangling gate between two species offers the freedom to select ions with different strengths for different tasks, and to transfer information from one to the other depending on the task at hand. Such a gate is an essential element in quantum logic spectroscopy, quantum networking and quantum information processing.

$^{43}Ca^{+}$ and $^{88}Sr^{+}$ are two species well-suited for different aspects of quantum computing, and have transition frequencies only 20 THz apart. Therefore a two-qubit $\sigma_z \otimes \sigma_z$ gate may be driven on both species simultaneously using a single pair of Raman beams. I will present such a gate with fidelity 99.8(2)%, pushing mixed-species gate fidelities close to the best single-species entangling gates (99.9%). We use different methods to perform a full characterisation of this gate: with two-qubit randomised benchmarking we measure a fidelity of 99.72(6)% with sequences involving up to 75 entangling gates, or 30 interleaved entangling gates. From gate-set tomography we deduce a fidelity of 99.4(4)% for the two-qubit operations.

I will further present progress towards a mixed-species Mølmer-Sørensen gate on the same crystal, comparing the two methods.

Q 24.4 Wed 12:00 e001

Towards a Scalable Fault-Tolerant Ion-Based Quantum Processor — •Daniel Pijn, Janine Hilder, Alex Stahl, Max Orth, Alex Müller, Björn Lekitsch, Ferdinand Schmidt-Kaler, and Ulrich Poschinger — QUANTUM, Univ. Mainz, Institute of Physics, Staudingerweg 7, 55128 Mainz, Germany

We present steps towards the experimental realization of an error correction algorithm in a shuttling-based trapped-ion quantum processor. Ions are stored in a segmented linear Paul trap with one static laser interaction zone (LIZ). Addressed single- and two-qubit gate operations are performed by selectively transporting ions into the LIZ. The qubit register can be reconfigured by splitting, merging [1], and swapping [2] of ion crystals. Using this setup, we have previously prepared a four-qubit GHZ state [3], and used entangled ion pairs to measure magnetic field differences with a sensitivity of 12 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$ [4]. Current work aims at implementing a topological error correction circuit [5]. We measure stabilizer operators on four data qubits using an additional ancilla and flag qubit [6]. Alongside the latest results we discuss our efforts to maintain the required degree of qubit coherence.

[1] Walther et al., Phys. Rev. Lett. 109, 080501 (2012)
[2] Kaufmann et al., Phys. Rev. A 95, 052319 (2017)
[3] Kaufmann et al., Phys. Rev. Lett. 119, 150503 (2017)
[4] Ruster et al., Phys. Rev. X 7, 031050 (2017)
[5] Bermudez et al., Phys. Rev. X 7, 041061 (2017)
[6] Bermudez et al, arXiv: 1810.09199 [quant-ph]

Q 24.5 Wed 12:15 e001

High-fidelity two-qubit gates using robust pulsed dynamical decoupling — Patrick Barthel[1], Jorge Casanova[2], •Patrick Huber[1], Theeraphot Sriarunothai[1], Martin Plenio[3], and Christof Wunderlich[1] — [1]Department Physik, Universität Siegen, 57068 Siegen, Germany — [2]Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain — [3]Institut für Theoretische Physik, Albert-Einstein-Allee 11, Universität Ulm, 89069 Ulm, Germany

Continuous or pulsed dynamical decoupling (DD) has been successfully used to extend the coherence time of qubits, for example in trapped atomic ions. A recently proposed, novel DD sequence is presented that not only extends the coherence time, but also results in a tunable two-qubit phase gate with high fidelity. Using both motional modes of a two-ion crystal, it allows for higher gate speeds than comparable single-mode gates [1]. We report on the experimental realization of a $\frac{\pi}{4}$-gate with a fringe contrast up to 99(2)%, applying this sequence on a set of two $^{171}Yb^{+}$ ions in a linear Paul trap using microwave driving fields. The interaction between motional and internal qubit states necessary for conditional quantum logic is provided by magnetic gradient induced coupling (MAGIC) [2]. We demonstrate the applicability of the sequence for Controlled-NOT operations and the creation of Bell states, as well as its robustness to errors in Rabi frequency, trap frequency and to ion temperature.

[1] I. Arrazola et al., Phys. Rev. A **97**, 052312 (2018)
[2] T. Sriarunothai et al., Quantum Sci. Technol. **4** (2019) 015014

Q 24.6 Wed 12:30 e001

Robust and resource efficient entangling gate with amplitude modulation of microwave near-fields — •Giorgio Zarantonello[1,2], Henning Hahn[1,2], Jonathan Morgner[1,2], Marius Schulte[3], Amado Bautista-Salvador[2,1], Reinhard Werner[3], Klemens Hammerer[3], and Christian Ospelkaus[1,2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — [2]PTB, Bundesallee 100, 38116 Braunschweig — [3]Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstr. 2, 30167 Hannover

The DiVincenzo criteria [1] define the requirements for quantum computing specifically the need for a universal set of quantum gates. This is satisfied by the ability to perform single qubit gates and a two qubit entangling gate. We implement such operations using near-field microwaves [2] in a surface-electrode ion trap using embedded microwave conductors. In this talk we will present a coherent control method based on amplitude modulation of the microwaves which has so far allowed to obtain Bell state infidelities in the 10^{-3} range [4].

[1] D. P. DiVincenzo, Fortschritte der Physik, **48**, 771-783(2000)
[2] C. Ospelkaus *et al.*, Nature **476**, 181 (2011)
[3] D.J. Wineland *et al.*, J. Res. NIST. **103**, 259-328 (1998)
[4] G. Zarantonello *et al.*, arXiv:1911.03954 [quant-ph]

Q 24.7 Wed 12:45 e001

Cryogenic surface-electrode ion trap apparatus for $^{9}Be^{+}$-ions — •Timko Dubielzig[1], Sebastian Halama[1], Giorgio Zarantonello[1,2], Henning Hahn[1,2], Amado Bautista-Salvador[2], and Christian Ospelkaus[1,2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — [2]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig

We recently commisioned a cryogenic surface electrode ion trap with integrated microwave conductors for near-field quantum control of $^{9}Be^{+}$. This trap has been operating since late November 2019 and we will present the first results. This system is a very promising environment for analog quantum simulators and for quantum logic applications. The trap is mounted to an ultra-low vibration interface, leading to a measured upper limit on vibrations caused by the cryocooler of 8 nm RMS. We operate the trap at a bias field of 223 G, where the transition between |F=2,mF=1> and |F=1,mF=1> is first-order field independent for long coherence times. Immediate perspectives for the experiment include the realization of a high-fidelity two-qubit gate, based on the recent advances in our room temperature setup, and 2D arrays of ion traps interacting via the remote Coulomb interaction as well as the implementation of effective magnetic interactions through integrated near-field microwave methods.