Q 2: Quanteninformation (Atome und Ionen I)

Zeit: Montag 14:00–16:00 Raum: 1B

Gruppenbericht Q 2.1 Mo 14:00 1B

Entanglement and Quantum Networking with Trapped Atoms — •David Moehring[1,2], Jörg Bochmann[1], Dzmitry Matsukevich[2,3], Peter Maunz[2,3], Martin Mücke[1], Tobias Müller[1], Steven Olmschenk[2,3], Holger Specht[1], Bernhard Weber[1], Christopher Monroe[2,3], and Gerhard Rempe[1] — [1]Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany — [2]FOCUS Center and Department of Physics, University of Michigan, Ann Arbor, MI 48109-1040, USA — [3]JQI and Department of Physics, University of Maryland, College Park, Maryland 20742, USA

Distant, entangled qubits represent a universal resource for distributed quantum computing. One method to entangle two distant particles involves detecting a single photon from each particle after the photons have interfered. When two atoms each become entangled with an emitted single photon, subsequent interference and detection of these photons can leave the trapped atom qubits in an entangled state. Although this entanglement is probabilistic, it is not post-selective and therefore can be utilized for long-distance quantum communication and large-scale quantum computation.

I will discuss the experimental realization of remote-entanglement of two individually trapped ions separated by one meter [1] as well as current efforts toward deterministic entanglement via atoms trapped within high-finesse optical cavities [2,3].

[1] Moehring *et al.*, Nature **449**, 68 (2007)
[2] Wilk *et al.*, Science **317**, 488 (2007)
[3] Hijlkema *et al.*, Nature Physics **3**, 253 (2007)

Q 2.2 Mo 14:30 1B

Ion trap quantum gates with amplitude-modulated laser beams — •Christian Roos — Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Otto-Hittmair-Platz 1, 6020 Innsbruck, Österreich

In ion traps, entangling gate operations can be realized by a bichromatic pair of laser beams that collectively interact with the ions. A new method of modelling the laser-ion interaction is introduced that turns out to be superior to standard techniques for the description of gate operations on optical qubits. The treatment allows for a comparison of the performance of gates based on $\sigma_z \otimes \sigma_z$ and $\sigma_\phi \otimes \sigma_\phi$ interactions on optical transitions where the bichromatic laser field can be realized by an amplitude-modulated laser resonant with the qubit transition [1]. Shaping the amplitude of the bichromatic laser pulse is shown to make the gates more robust against experimental imperfections. An experimental implementation of the gate using a pair of calcium ions have shown very promising results [2].

[1] C. F. Roos, arXiv:0710.1204, accepted for publication in New. J. Phys.
[2] J. Benhelm, G. Kirchmair, C. F. Roos, R. Blatt, manuscript in preparation.

Q 2.3 Mo 14:45 1B

Towards fault-tolerant quantum computing with trapped ions — •Jan Benhelm[1,2], Gerhard Kirchmair[1,2], Christian F. Roos[1,2], and Rainer Blatt[1,2] — [1]Institut für Experimentalphysik, Innsbruck — [2]Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Innsbruck

For fault-tolerant computation, it is commonly believed that error thresholds ranging between 10^{-4} and 10^{-2} will be required depending on the noise model and the computational overhead for realizing the quantum gates. Up to now, all experimental implementations have fallen short of these requirements.

Here, we report on the experimental realization of a Mølmer-Sørensen type entangling gate operation with a fidelity of 99.3% which together with single-qubit operations forms a universal set of quantum gates. The gate operation is performed on a pair of qubits encoded in two trapped calcium ions using a single amplitude-modulated laser beam interacting with both ions at the same time. A robust gate operation, mapping separable states onto maximally entangled states, is achieved by adiabatically switching on and off the laser-ion coupling. We analyse the performance of a single gate and concatenations of up to 21 gate operations.

Q 2.4 Mo 15:00 1B

Deterministic Entanglement Swapping with Trapped Ions — •Mark Riebe[1], Thomas Monz[1], Kihwan Kim[1], Alessandro Villar[2], Philipp Schindler[1], Markus Hennrich[1], and Rainer Blatt[1,2] — [1]Institut für Experimentalphysik, Universität Innsbruck, Austria — [2]Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Austria

Entanglement is a key feature in the field of quantum information processing, as it allows for quantum communication, secret key sharing and quantum computation. Many of these applications require entangled states distributed among distant locations. Distribution of entangled states can be aided by a scheme known as entanglement swapping [1]. We demonstrate this scheme with a string of four trapped ^{40}Ca-ions, which carry quantum information in their internal states $S_{1/2}$ and $D_{5/2}$ [2]. Initially, ion pairs 1,2 and 3,4 are each prepared in the Bell state $\Psi^- = (|DS\rangle - |SD\rangle)/\sqrt{2}$. Then, ion 1 and 4 are measured in the Bell basis. The result of this measurement is perfectly correlated with the Bell state into which the previously unentangled ions 2 and 3 are projected. We make use of this fact and apply further rotations to ion 3 conditioned by the Bell measurement result, such that ions 2 and 3 are deterministically mapped to the state Ψ^-. This is confirmed by determining the final state of ions 2,3 by state tomography, which proves that we prepare the state Ψ^- with a fidelity of 79%.

[1] J. W. Pan et al., Phys. Rev. Lett. 80, 3891 (1998).
[2] F. Schmidt-Kaler et al., Appl. Phys. B 77, 789 (2003).

Q 2.5 Mo 15:15 1B

Three-qubit Toffoli gate with trapped ions — •Thomas Monz[1], Kihwan Kim[1], Wolfgang Hänsel[1], Alessandro Villar[2], Philipp Schindler[1], Mark Riebe[1], Markus Hennrich[1], and Rainer Blatt[1,2] — [1]Institut für Experimentalphysik, Universität Innsbruck, Austria — [2]Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Austria

Quantum algorithms are usually decomposed into a sequence of gate operations each acting only on a few qubits. A well-known set for this purpose is a two-qubit controlled NOT (CNOT) gate combined with single qubit rotations. However, gates that connect more than two qubits could facilitate quantum computations. One example is the three-qubit Toffoli gate, which is a valuable tool for quantum error correction. The Toffoli gate acts on a register of two control qubits $|c_1, c_2\rangle$ and one target qubit $|t\rangle$ as $|c_1, c_2, t\rangle \rightarrow |c_1, c_2, (c_1 \wedge c_2) \oplus t\rangle$. We implement this gate with a string of trapped ions, where we use the ion's internal states as qubits and manipulate these with suitable laser pulses. Our implementation relies on an extension of the Cirac-Zoller gate proposal [1]: First a carefully designed sequence of laser pulses encodes the information $(c_1 \wedge c_2)$ in one of the ion string's vibrational modes. Then a CNOT gate between the target qubit and the vibrational mode realizes the operation $|t\rangle \rightarrow |(c_1 \wedge c_2) \oplus t\rangle$. Finally, the initial encoding procedure is reversed. We analyze the Toffoli gate operation by quantum process tomography, and obtain a mean gate fidelity of 79%.

[1] J. I. Cirac and P. Zoller, Phys. Rev. Lett. 74, 4091 (1995).

Q 2.6 Mo 15:30 1B

Coupling trapped ions via transmission lines — Rob Clark[1,2], Sankaranarayanan S[1], •Nikos Daniidilis[1], and Hartmut Häffner[1] — [1]Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Innsbruck, Österreich — [2]Center for Ultracold Atoms, Massachusetts Institute of Technology, START project Cambridge, MA, USA

An oscillating trapped ion induces oscillating image charges in the trap electrodes. If this current is send to the electrodes of a second trap, it influences the motion of an ion in the second trap. The expected time for a complete exchange of the ion motions is 1 ms for a trap with a characteristic size of 50 μm. This inter–trap coupling may be used for scalable quantum computing, cooling ion species that are not directly accessible to laser cooling, for the non-invasive study of superconductors, and for coupling an ion–trap quantum computer to a solid–state quantum computer, e.g. a system of Josephson junctions.

We will discuss the feasibility of experiments towards these goals with trapped Calcium ions. The most relevant source of decoherence is heating of the ion motion due to noise in the trap electrodes (e.g. Johnson–noise). By operating ion traps at cryogenic temperatures, heating will be greatly reduced, allowing the coherent coupling of two ions. In this context, we will present results from currently operating planar traps, as well as efforts in developing microfabricated planar traps. In particular, we will discuss the influence of an electrically floating coupling electrode on trap performance.

Q 2.7 Mo 15:45 1B

Long-distance atom-photon entanglement and its coherence properties — •Michael Krug[1], Wenjamin Rosenfeld[1], Fred Hocke[1], Florian Henkel[1], Andreas Deeg[1], Christian Jakob[1], Markus Weber[1], and Harald Weinfurter[1,2] — [1]Sektion Physik, Ludwig-Maximilians-Universität München, Schellingstrasse 4, D-80799 München — [2]Max-Planck Institut für Quantenoptik, D-85748 Garching

Long-distance Atom-Photon Entanglement: The distribution of entanglement between quantum memories at remote locations is one major challenge for the first demonstration of a quantum repeater. Entanglement between matter and light [1] is crucial for achieving this task. Here we report the observation of entanglement between a single trapped atom and a single photon, separated 300 m via an optical fiber. The entanglement is verified by appropriate correlation measurements of the atom-photon pair after communicating the photon through the fiber. In addition we analyzed the temporal evolution of the atomic density matrix after projecting the atom-photon pair via a state measurement of the photon onto a well defined atomic spin state. We find that the atomic Zeeman qubit decoheres after 100 μs. Our results represent important steps towards the realization of entanglement between single neutral atoms at distances of several 100 m.

[1] J. Volz, M. Weber, D. Schlenk et al., Phys. Rev. Lett. **96**, 030404 (2006).