Quantum Information Using Microwave Manipulation of Laser Cooled Ionic Spin Chains

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Motivation

Strings of laser cooled ions stored in linear Paul traps have promising potential in the fields of quantum information and simulation [1, 2]. They provide a system which can be efficiently screened from a decoherence inducing environment, accurately prepared in a large variety of states and manipulated with high accuracy. Furthermore, state detection can be achieved with almost unit efficiency.

Spin-Spin Coupling

The Hamiltonian of linearly trapped ions exposed to a magnetic gradient can be described as [4-5]

\[ H = \sum_n \frac{\mu_n}{r_n} + \frac{1}{2} \sum_{n,m} J_{nm} \sigma_n \cdot \sigma_m + \text{c.c.} \]

As a third effect the internal state is coupled to the equilibrium positions of all other ions, mediated by Coulomb repulsion. This can be understood as a long range spin-spin \(\sigma\) coupling of the ions internal states induced by the gradient, which is proportional in strength to the square of the magnetic gradient [4]. The spin-spin coupling is useful for building a quantum computer and for quantum simulations, e.g., for studying quantum phase transitions.

Spin-Spin Coupling Constants

Magnetic Gradient Induced Coupling (MAGIC) [4] is a first order, insensitive to thermal excitation of motional states and avoids several difficulties often associated to laser and light induced phenomena (lifetime, spontaneous decay, pointing-, amplitude- and frequency-stability).

We measured the spin spin coupling in a two ion string stored in a macroscopic Paul trap using a Ramsey phase method with intermittent Spin Echo pulses to cancel unwanted coupling to the environment or drifts of the resonance frequency due to changing magnetic fields.

The segmented Gradient Microtrap

A large magnetic gradient results in both large frequency separation and coupling constants. Therefore we developed a coil design which was optimized with respect to gradient per dissipated heat.

Segmented Trapping

Our trap is a three layer design. The two outer layers were designed, simulated and implemented by the group of Schmids Kaler, University of Mainz.

The outer layers are made of 125 \(\mu\)m thick \(\text{Al}_2\text{O}_3\), and provide RF electrodes for radial trapping and 32 segmented DC electrodes for tailoring arbitrary axial trapping potentials in a wide (500 \(\mu\)m) trapping zone and a narrow (250 \(\mu\)m) experiment zone.

The system is assembled and under UHV. The round-trip coil resistances of the gradient coils are around 1 Ohm, permitting up to 5 A steady state current (corresponding to ca. 5 T/m), and potentially a factor of 10 more when pulsed. We are currently setting up the system, check for neutral atom fluorescence, and attempt trapping.

Nuclear Spin Qubits

We propose to encode qubits in both electronic and nuclear spins of trapped atomic ions for QC and quantum simulations. We consider quantum logic operations on ions in the Paschen-Back regime with qubits encoded in nuclear spins I and auxiliary qubits in electron spins S = 1/2. This combines the long decoherence time of nuclear spins with efficient manipulation and readout using electron spins.

Quantum Information is stored in nuclear spins and is only swapped into electronic spins for single-qubit gates and conditional quantum dynamics with two and more ions. Thus, quantum information remains well protected from ambient noise fields that otherwise would give rise to decoherence.

To achieve both high magnetic offset fields and gradients we propose the combination of surface traps and a Halbach magnet. While the first allows to create a high and switchable gradient, the latter uses permanent magnets to create static magnetic fields exceeding the flux density of the permanent magnets.

Outlook

Once up and running, the experiment opens up a wide range of possibilities to create tailored interaction for quantum simulations and quantum information. As one application, we proposed an efficient implementation to create singlet states [7] which are interesting for example in the one way quantum computer [8].

Literature