Cooling ion strings to the vibrational ground state

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Trapped and laser cooled ions in Paul traps are proposed for the implementation of quantum information processing. Internal electronic states of individual ions serve to hold the quantum information (qubits) and an excitation of common vibrational modes provides the coupling between qubits, which is necessary for quantum logic operations between qubits.

We pursue experiments with ions in a linear Paul trap with the goal of small-scale quantum information processing. For this, we have to consider a number of issues, which are discussed in this presentation: (i) How to reach the ground state for one vibrational mode [1], (ii) how to construct a trap where ions are only slowly heating up [2]. (iii) To yield the full information on the electronic state of the ion string, and to individually manipulate each ion in the string, the ions have to keep a certain distance which is given by the optical resolution of the imaging and addressing system [3]. (iv) The vibrational motion for a string of N ions is described by 3 N modes. A residual thermal phonon distribution in the other modes leads to reduced fidelity of the gate operations which are performed on the ground state cooled (axial) mode.

The motional ground state of two ions in the linear trap ($\omega_{axial} \approx$ 700kHz, $\omega_{radial} \approx$ 1.7MHz) is reached with resolved sideband cooling on the $S_{1/2}-D_{5/2}$ transition, with additional excitation of the $D_{5/2} - P_{3/2}$ transition (see Fig. 1). Note that at 700 kHz axial frequency, the inter-ion distance of $\approx$7 μm still allows individual addressing.

To probe the ground state population, we excite the motional sidebands at $\delta\omega = \pm\omega_{trap}$, and compare the resulting excitation $D_{5/2}$ population. As an example we show in Fig. 2 the cooling result for the radial mode of two ions, the frequency is centered around the radial vibration mode frequency. We transfer 98.5(1.5)% of the population to the vibrational ground state.

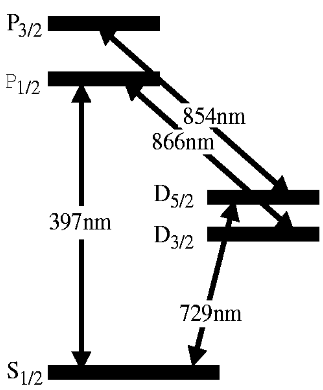

Figure 1: Relevant energy levels of $^{40}Ca^+$ and the corresponding transition wavelengths. The D levels are metastable with 1 s lifetime. Superpositions of the $S_{1/2}$ and $D_{5/2}$ states are used to implement qubits.

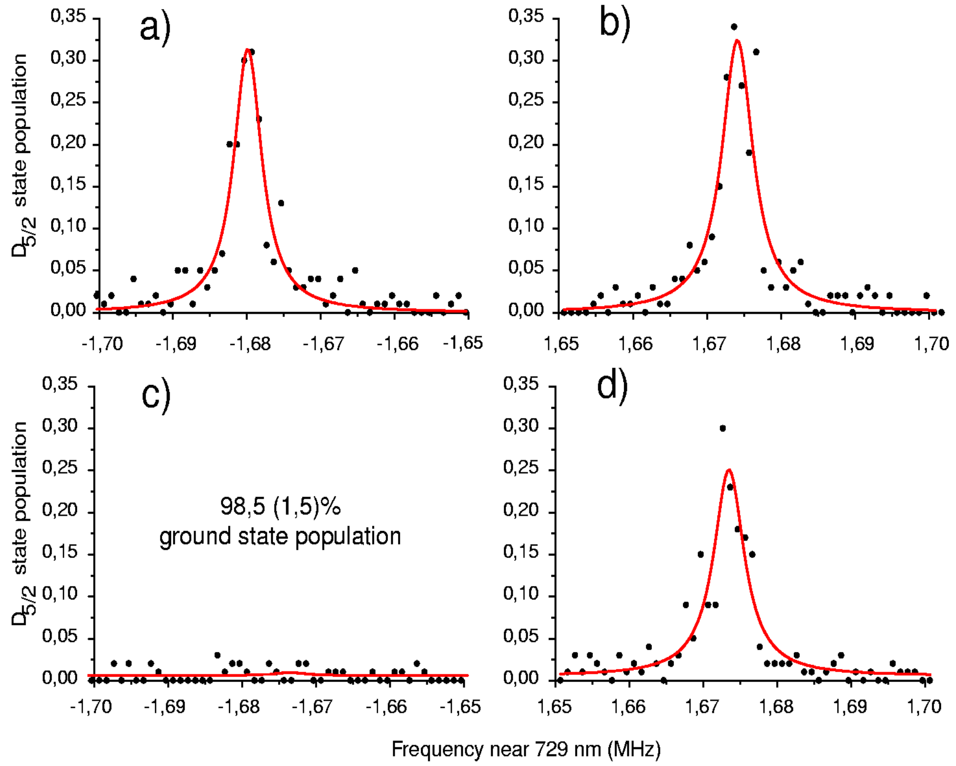

Figure 2: Sideband excitation spectrum on the $S_{1/2}(m=-1/2) \leftrightarrow D_{5/2}(m=-5/2)$ transition. a), b): Red and blue sideband after Doppler cooling on the $S_{1/2} - P_{1/2}$ transition. c), d): Excitation of the red and blue sideband after sideband cooling.

The heating rates of various vibrational modes have been investigated and we found 20 to 40 ms per phonon. The motional heating is thus slow compared with the timescale of coherent dynamics [4]. We will discuss examples of coherent dynamics on ions strings, in order to generate entanglement.

In the last part of the presentation, we discuss the optimum range of parameters for a linear Paul trap, in order to fulfill all conditions above.

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