TOWARDS QUANTUM COMPUTATION WITH TRAPPED CALCIUM IONS

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Abstract For quantum information experiments we have cooled one and two ^{40}Ca^{+} ions to the ground state of vibration with up to 99.9% probability, using resolved sideband cooling on the optical $S_{1/2}$ -$D_{5/2}$ quadrupole transition. Implementing a novel cooling scheme based on electromagnetically induced transparency on the $S_{1/2}$ -$P_{1/2}$ manifold we have achieved simultaneous ground state cooling of two motional sidebands 1.7 MHz apart. Coherent quantum state manipulation on the $S_{1/2}$ -$D_{5/2}$ quadrupole transition at 729 nm was demonstrated and up to 30 Rabi oscillations within 1.4 ms have been observed starting from the motional ground state and from the $n = 1$ Fock state. In a linear rf-trap two ions were cooled to the ground state of motion and individual addressing of the ions with laser pulses is achieved.

1. INTRODUCTION

Quantum information processing operations put severe demands on the experimental techniques. For example, a two-qubit quantum gate requires two strongly interacting quantum systems, non-interacting with the environment. A quantum logic gate based on trapped ions was proposed by Cirac and Zoller. This scheme requires the ions to be trapped in a linear radio-frequency (Paul) trap and cooled to the motional ground state of their (collective) motion [1]. The work reported here is based on ^{40}Ca^{+} ions. The light sources for all transitions involved are derived from diode and solid state lasers. With two different traps we have investigated several ways to cool one or two ions to the ground state of motion. Starting from this pure initial state, we perform coherent quantum manipulations of a single ion and of individual ions in an ion string.

2. EXPERIMENTAL SETUP

Quantum information processing requires that atomic transitions are available with two long lived states which can serve to encode the quantum bit (qubit). The relevant levels of Ca^+ are shown schematically in Fig. 1. Doppler cooling is achieved by driving the $S_{1/2}$ – $P_{1/2}$ dipole transition at 397 nm with a frequency-doubled Ti:Sapphire laser that is red detuned from the transition line center by about 20 MHz, the natural line width of the $P_{1/2}$ level. To prevent pumping to the $D_{3/2}$ level, the ions are simultaneously irradiated with a diode laser at 866 nm driving the $D_{3/2}$-$P_{1/2}$ transition (Fig. 1 (a)). With a magnetic field of about 4 Gauss we produce a well defined quantization axis and split the Zeeman sublevels. Using an additional σ^+ polarized beam at 397 nm the pure electronic state $S_{1/2}$, $m = 1/2$ of the ion(s) can be prepared.

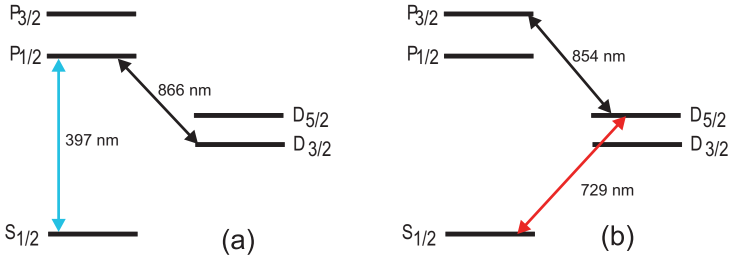

Figure 1 Relevant levels and transitions in $^{40}Ca^+$ for (a) Doppler cooling and state detection and for (b) resolved sideband cooling and coherent manipulations which are performed on the effective two level system (qubit) formed by $S_{1/2}$ and $D_{5/2}$ levels.

The $S_{1/2}$ ground state and the metastable $D_{5/2}$ state with a natural lifetime of about 1 s serve as the two qubit levels (Fig. 1(b)). Quadrupole transitions between these levels are driven with a Ti:Sapphire laser at 729 nm, stabilized with the Pound-Drever-Hall method to a high finesse cavity. To maintain the coherence necessary for qubit manipulations this laser has to be highly stable. We have determined an upper bound of 76(5) Hz (FWHM) for the effective linewidth of our laser system, by observing the fringe contrast in high resolution Ramsey spectroscopy on the $S_{1/2}, m = -1/2$ – $D_{5/2}, m = -5/2$ transition as a function of the time delay between the two excitation pulses [2]. The laser beams at 397 nm and 866 nm used for Doppler cooling also provide highly efficient state detection with the quantum jump technique [3]. Many photons are scattered and observed at 397 nm if the ion is in the ground state. On the other hand, if the ion is in $D_{5/2}$, this level is decoupled from the excitation and no fluorescence photons will be emitted. Although only a small fraction (ca. 10^{-2}) of these fluorescence photons is collected by a lens and imaged onto a photomultiplier with a quantum efficiency of about 10%, one can distinguish the two qubit states within 2 ms of detection time. This allows us to measure the state of our qubit with practically 100% efficiency.

In our experiments we use two different ion traps. The first trap is a regular spherical Paul trap with motional frequencies of up to 4.5 MHz and 2 MHz along the axis of symmetry and in the ring plane, respectively. Doppler cooling leads to average occupation numbers $\bar{n} = 2(4)$ for the axial (radial) harmonic oscillator, making this trap a good test bed for cooling and coherent control techniques with just one ion. For quantum information processing we use a linear quadrupole trap with secular frequencies of 2 MHz in the radial direction and up to 700 kHz in the axial direction. For a string of up to 4 ions this leads to inter-ion distances $\geq 5\mu$m, well above the diffraction limit of our laser beams. Under these conditions we are able to individually address ions within such a string, at the expense of a higher average occupation number ($\bar{n} \simeq 25$ in the axial direction) after Doppler cooling.

3. INDIVIDUAL ADDRESSING

For the Cirac-Zoller [1] gate the internal states of ions in a string have to be manipulated individually. One obvious limitation of this approach is that the size of the focus is limited by diffraction to roughly one micron and so the minimum distance between ions has to be larger than that number. A given minimum spacing of ions restricts the maximum center of mass (COM) frequency for a given number of ions along the axis of symmetry [4]. If four ions of Ca^+ should not be closer together than 5 μm, the maximum COM frequency is about 700 kHz The spatial resolution of our imaging system [5] is about 2 μm. For individual addressing we use the imaging lens in reverse and superimpose the addressing beam at 729 nm with the imaging channel on a dichroic mirror [6]. The beam is steered over the ions with an electrooptic deflector driven by a high voltage amplifier stage which allows us to switch from one ion to the other in a few μs. We have checked the beam diameter and pointing stability of our system by mapping the Rabi frequency on the $S_{1/2}$-$D_{5/2}$ transition versus the beam displacement and found a 1/e width of 3.7(0.3) μm for this excitation. If we apply a π-pulse to the ion addressed, the probability of exciting a neighboring ion in the ground state and 5 μm away would be about 1%.

4. GROUND STATE COOLING

For ground state cooling [7, 8] we use resolved sideband cooling on the $S_{1/2}$-$D_{5/2}$ quadrupole transition [9]. The slow spontaneous decay on a bare quadrupole transition would result in long cooling times. Therefore, the cooling rate is greatly enhanced by (i) strongly saturating the transition and (ii) shortening the lifetime of the excited state by coupling it to a dipole-allowed transition. For cooling a single ion in the circular trap, the $S_{1/2}(m=1/2)-D_{5/2}(m=5/2)$ transition, well resolved in frequency from all other possible transitions by the applied magnetic field, is excited with about 1 mW of light focused to a waist size of 30 μm at the position of the ion. At the same time, the decay rate back to the ground state is increased by exciting the $D_{5/2}(m=5/2)-P_{3/2}(m=3/2)$ transition. The intensity of this quenching laser at 854 nm is adjusted for optimum cooling during the experiment. Optical pumping to the $S_{1/2}(m=-1/2)$ level is prevented by occasional short laser pulses of σ^+ polarized light at 397 nm. The duration of those pulses is kept at a minimum to prevent unwanted heating. The ground state occupation is found by comparison of the on-resonance excitation probability for red and blue sideband transitions [9]. In the spherical Paul-trap we obtained up to 99.9% of motional ground state occupation within 6 ms (see Fig. 2).

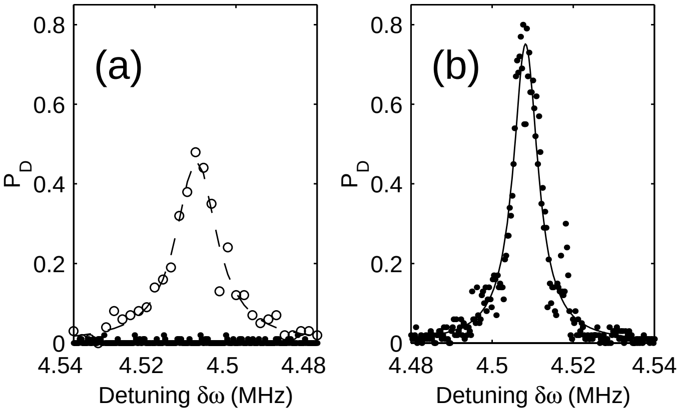

Figure 2 Red and blue sidebands of the axial mode (at 4.51 MHz) of one ion after Doppler cooling (dashed) and after resolved sideband cooling (solid). From the ratio of sideband strengths we determine 99.9% ground state occupation.

All earlier successful ground state cooling experiments were plagued by an unexpectedly high motional heating (see [10] and references therein). In our setup we find a motional heating rate of one phonon in 190 ms for a trap frequency of 4 MHz, two orders of magnitude smaller than in the trap used at NIST for the ^{9}Be$^+$ experiment. While this is still a much higher heating rate than expected from black body radiation, it happens on a timescale much longer than the time typically needed for quantum logic gates (we estimate an upper limit of 200 μs for one CNOT gate).

In separate experiments in our linear trap, we also cooled all motional modes of two ions to the ground state [11]. Cooling only one of the 6 motional modes at a time, we achieved at least 95% ground state occupation for all modes using the addressing channel to illuminate one of the two ions with the cooling radiation. The second ion is cooled sympathetically due to the strong inter-ion Coulomb coupling [2].

5. EIT COOLING

Resolved sideband cooling only leads to very low temperatures if the red sideband is excited with a narrow excitation bandwidth. Otherwise nearby nonresonant transitions (e.g. carrier transitions) will lead to unwanted excess heating and severely increase the final temperature of the ion(s). Unless sideband frequencies are degenerate, this limits resolved sideband cooling to one motional sideband at a time, resulting in involved cooling schemes. Moreover the phonons scattered in the process of cooling one motional mode will reheat the other modes. Although for a Cirac-Zoller gate only the motional mode that is used as the 'quantum-bus' has to be cooled to a very high degree, the other motional modes must be cooled into the Lamb-Dicke regime [12]. To reach this regime by Doppler cooling would require trap frequencies of 10 MHz or higher and result in an ion spacing that is hard to optically resolve. This leads to a trade-off between addressing individual ions and sufficiently cooling all vibrational modes of a string. In our experiments with two or more ions in the linear trap we decided to maintain good conditions for individual addressing and limited our axial COM frequency to 700 kHz. Under these conditions it was desirable to find a cooling technique that is not as narrow-band as resolved sideband cooling but has a lower cooling limit than Doppler cooling. A very recent proposal to use electromagnetically induced transparency (EIT) for the cooling of trapped particles [13] promised to cool the ion deeply into the Lamb-Dicke regime for all motional degrees of freedom simultaneously. We adapted this cooling scheme for the case of the [S$_{1/2}$, P$_{1/2}$] four level system in Ca$^+$ that we also use for Doppler cooling. The manifold is dressed with a σ^+-polarized beam at 397 nm, blue detuned by $\Delta_\sigma \simeq 70$ MHz (3.5 linewidths of the S-P transition), that connects the S$_{1/2}$, m=-1/2 with the P$_{1/2}$, m=1/2 level. Under these circumstances a second low-intensity π-polarized beam experiences an absorption (Fano-) profile as depicted in Fig. 3(a).

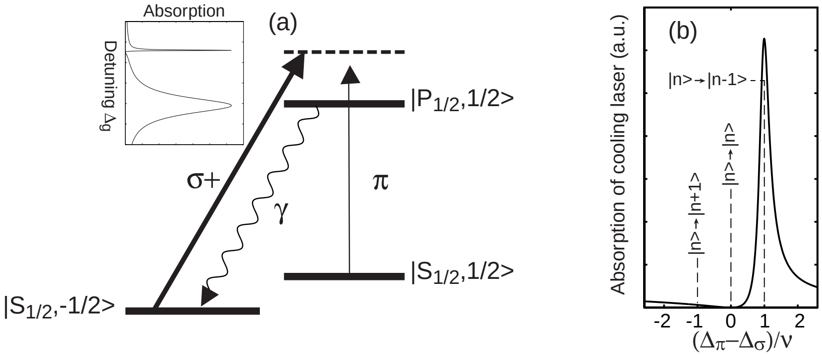

Figure 3 (a) Level scheme of the $S_{1/2}$-$P_{1/2}$ manifold and lasers used for EIT cooling. A strong σ^+ polarized beam creates a Fano-type absorption profile for a weak π-polarized beam. (b) By tuning the π-polarized beam to $\Delta_{pi} = \Delta_{sigma}$ and choosing the AC-Stark shift equal to the trap frequency, cooling red sideband transitions are much more probable than heating blue sideband transitions, and the carrier is completely suppressed.

In addition to the usual line profile around $\Delta_\pi = 0$, a dark resonance (EIT) is created at $\Delta_\pi = \Delta_\sigma$, and a bright resonance appears at $\Delta_\pi = \Delta_\sigma + \delta$ where δ is the AC Stark shift due to the σ^+-polarized beam. For cooling the π-polarized beam is tuned to $\Delta_\pi = \Delta_\sigma$ and δ is adjusted to match the trap frequency. This creates an asymmetry in absorption for carrier and sidebands: The carrier is almost completely suppressed due to the dark resonance, the blue sideband is in the shallow wing of the profile, but the red sideband is greatly enhanced by the bright resonance, see Fig. 3(b). When we tuned the Stark-shift δ to be equal to one of the motional modes at 3.34 MHz we were able to cool this mode to 90% ground state occupation or $\bar{n} = 0.1$. Moreover, as sketched in Fig. 3(b) the bright resonance can have a substantial width and the red sideband need not necessarily coincide exactly with the maximum of the bright resonance to get a cooling effect. This opens the possibility to cool several motional modes *simultaneously*, as long as they are not too far apart in frequency.

To demonstrate simultaneous cooling of two vibrational modes with this method we chose two modes at 1.61 MHz and 3.34 MHz. The AC-Stark shift δ of the σ^+-beam was adjusted to be about 2.5 MHz, halfway between the two mode frequencies. With this settings we achieved 58% ground state occupation ($\bar{n} = 0.85$) in the mode at 1.61 MHz and 74% ($\bar{n} = 0.35$) at 3.34 MHz. From this result we estimate that we can

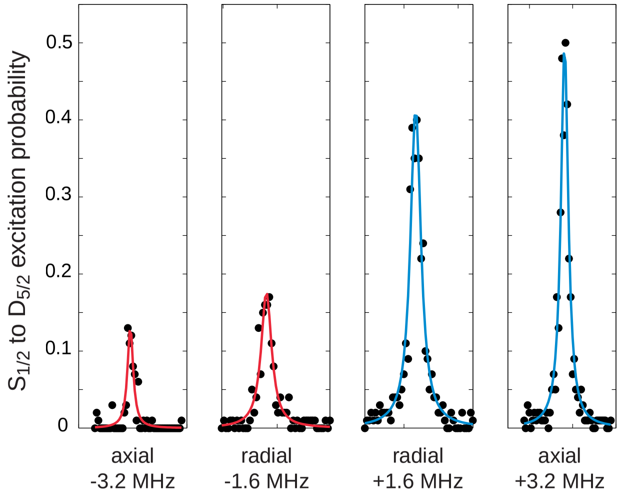

Figure 4 Simultaneous cooling of two vibrational modes with an oscillation frequency difference of 1.73 MHz. The sideband asymmetry corresponds to 58% ground state occupation ($\bar{n} = 0.85$) in the mode at 1.61 MHz and 74% ($\bar{n} = 0.35$) at 3.34 MHz.

sufficiently and simultaneously cool all axial degrees of freedom of a string of up to 5 ions with a COM mode frequency of 700 kHz.

6. COHERENT MANIPULATIONS

For quantum information processing, it is important to know for how long coherent interaction with the ion(s) is possible. For this we cooled one ion to the ground state and then irradiated the ion with light at the blue sideband frequency (This interaction is used in a quantum gate to transfer the internal state of a qubit into the motion) [9]. We then monitored the occupation probability of the D-state versus the pulse length on the blue sideband. The same interaction was also used after preparing the ion in the $n = 1$ motional Fock state by a π-pulse on the blue sideband followed by a repumping pulse on the $D_{5/2}$-$P_{3/2}$ transition. As Fig. 5 shows, we were able to observe Rabi-flops for both initial motional states with a contrast of better than 50% for 1 ms. The ratio of Rabi-frequencies is $\sqrt{2}$ as expected for this kind of interaction in the Lamb-Dicke regime. These results make us confident that we should be able to apply gate pulses equivalent to at least 40 π-pulses before the fidelity of the total operation drops below 0.5. In our system motional heating is too slow to be the prime source of the observed decoherence, we rather attribute it to time dependent magnetic field fluctuations that

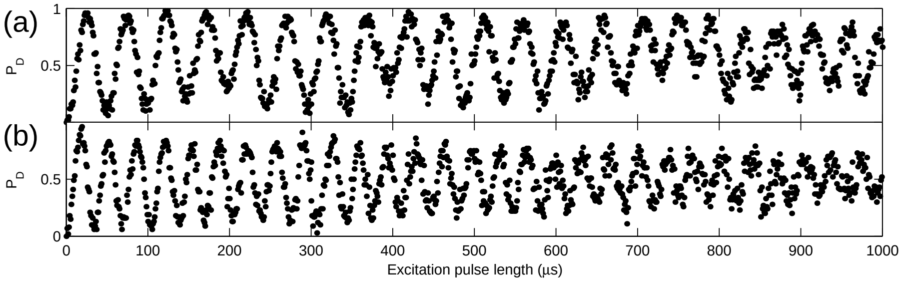

Figure 5 (a) Rabi-oscillations on the blue sideband for the initial motional state $|n = 0\rangle$. (b) Rabi-oscillations as in (a), but for $|n = 1\rangle$.

shift the levels, to slow vibrations in our setup that introduce a fluctuating Doppler-shift of the 729 nm beam, and to laser intensity fluctuations.

7. CONCLUSIONS AND OUTLOOK

We have demonstrated that we have all necessary ingredients to perform a two-bit quantum logic gate with trapped ions. The time scales in our system are well separated. The fastest characteristic time of 1 μs is given by the harmonic motion of the ion(s). A π-pulse on a motional sideband takes about 20 μs and, as stated above, the fidelity of coherent manipulations remains above 0.5 for times smaller than 1 ms. Our laser system would allow for coherent manipulations for at least 15 ms. Motional heating begins to play a role for times around 100 ms. The ultimate source of decoherence in our experiment is the 1 s lifetime of the $D_{5/2}$ state. In the near future we plan to use our ability to individually address ions to demonstrate a CNOT quantum logic gate with two ions and to create maximally entangled states with 2 and more ions. We also envision to perform small quantum algorithms and first experiments on error corrections with up to 5 ions.

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