Experimental Demonstration of Ground State Laser Cooling with Electromagnetically Induced Transparency

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Ground state laser cooling of a single trapped Ca^+ ion is achieved with a technique which tailors the absorption profile for the cooling laser by exploiting electromagnetically induced transparency. Using the Zeeman structure of the $S_{1/2}$ to $P_{1/2}$ dipole transition we achieve up to 90% ground state probability. The new method is robust, easy to implement, and proves particularly useful for cooling several motional degrees of freedom simultaneously, which is of great practical importance for the implementation of quantum logic schemes with trapped ions.

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One of the most promising avenues towards implementing the fundamental ingredients of a scalable quantum computer is, as of today, based on trapped ions. With a stringlike arrangement of several ions trapped in a radiofrequency (Paul) trap [1], deterministic entanglement between different ions [2] has been achieved. Individual addressing and state readout of ions in such a string with laser pulses has also been demonstrated [3]. Another fundamental requirement for quantum logic operations with trapped ions, following the original proposal [4], is the preparation of the ions in the quantum mechanical ground state of their motion by laser cooling. While a single trapped ion was laser cooled to the motional ground state as early as 1989 [5], ground state cooling of an ion string [6] and its combination with individual addressing [7] have only recently been demonstrated. The laser cooling methods used in those experiments are sideband cooling [5,7] and Raman sideband cooling [6], where a laser (or pair of lasers) exciting a narrow optical transition is detuned from the atomic resonance by the frequency of one motional quantum, thereby inducing transitions to lower-lying motional states until the ground state is reached.

Although for quantum gate operation only one mode out of the $3N$ motional degrees of freedom of an N-ion string is required to be cooled to the ground state, high-fidelity manipulation of the qubits requires the other modes to be deep inside the so-called Lamb-Dicke regime, where their residual vibrational amplitude is very small compared to the wavelength of the laser that induces optical transitions [8]. In conventional sideband and Raman sideband cooling, however, usually only one mode is cooled at a time, and the other modes are heated by spontaneous emission processes. A new cooling technique relying on electromagnetically induced transparency (EIT) [9] eliminates these difficulties largely by providing a larger cooling bandwidth, such that several modes can be cooled simultaneously, and by suppressing, through quantum interference, a large fraction of the heating processes. In this Letter we describe the first experimental demonstration of this technique and show that apart from its advantageous properties regarding heating and bandwidth it is also technically significantly simpler, thus making it a very favorable cooling method for quantum logic experiments with single ions.

The theoretical background of the method as described in [9] has to be adapted only slightly to be applied to our experiment. We implemented the scheme on the $S_{1/2} \rightarrow P_{1/2}$ transition of a $^{40}Ca^+$ ion, whose Zeeman sublevels form a four-level system. We denote the levels by $|S, \pm\rangle$ and $|P, \pm\rangle$; see Fig. 1. Three of the levels, $|S, \pm\rangle$ and $|P, +\rangle$, together with the σ^+- and π-polarized laser beams, form a system of the kind considered in [9], and the main modification is the fourth level whose effect will be discussed below.

The principle of the cooling is, briefly, that the stronger blue-detuned σ_+ light (the coupling laser) creates a Fano-type absorption profile for the π light (the cooling laser) which has a zero at $\Delta_\pi = \Delta_\sigma$ (this is the EIT condition) and a bright resonance corresponding to the dressed state $(\Omega_\sigma|S,-\rangle + 2\delta|P,+\rangle)/\sqrt{4\delta^2 + \Omega_\sigma^2}$ at $\Delta_\pi = \Delta_\sigma + \delta$, where $\delta = \frac{1}{2}(\sqrt{\Omega_\sigma^2 + \Delta_\sigma^2} - |\Delta_\sigma|) \simeq \Omega_\sigma^2/4\Delta_\sigma$ is the ac Stark shift created by the σ_+ light. By choosing $\Omega_\sigma \simeq 2\sqrt{\omega\Delta_\sigma}$, the ac Stark shift δ is made equal to the vibrational frequency ω of the mode to be cooled. Then, with the cooling laser tuned to $\Delta_\pi = \Delta_\sigma$, no π light is absorbed unless the ion provides a vibrational quantum,

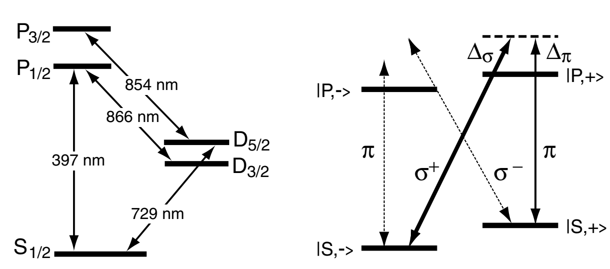

FIG. 1. Levels and transitions in $^{40}Ca^+$ used in the experiment (left). Zeeman sublevels of the $S_{1/2}$ and $P_{1/2}$ states and lasers relevant for the cooling (right). The σ^- light arises from the π laser beam not being orthogonal to the quantization axis. For EIT cooling, $\Delta_\pi = \Delta_\sigma$.

whereby the absorption probability is shifted to the bright resonance ("sideband absorption") and the ion's motion is cooled [10]. The spontaneous emission completing an absorption-emission cycle happens predominantly without a change of the motional state if the Lamb-Dicke condition is fulfilled. Since absorption without a change in motional energy ("carrier" absorption) is canceled by EIT, the heating which goes along with spontaneous emission after carrier absorption is also eliminated. This has consequences for both the mode to be cooled, for which a low final temperature can be reached, and for the other modes which are heated considerably less.

It has been shown that for the cooling technique used here [9], as for other methods [11], in the Lamb-Dicke regime and below saturation of the cooling transition the cooling process can be described by a rate equation of the form

$$\frac{d}{dt}\langle n\rangle = -(A_- - A_+)\langle n\rangle + A_+, \tag{1}$$

where $\langle n(t)\rangle$ is the mean vibrational excitation of the mode under consideration. The coefficients $A_\pm$ are derived from a full quantum mechanical master equation [9] and contain the quantum interference at $\Delta_\pi = \Delta_\sigma$. They can be interpreted as the rate coefficients for state-changing transitions induced by the cooling laser through sideband absorption and subsequent carrier emission [11]. When the scattering rate (linewidth times population of the upper state) for the cooling laser is denoted by $W(\Delta_\pi)$, we get for $\Delta_\pi = \Delta_\sigma$

$$A_\pm = \eta^2\cos^2(\phi)W(\Delta_\pi \mp \omega), \tag{2}$$

where $\eta = |\vec{k}_g - \vec{k}_r|a_0$ is the Lamb-Dicke parameter, with a_0 the rms size of the ground state of the harmonic oscillator and $\vec{k}_g$ ($\vec{k}_r$) the cooling (coupling) laser wave vector, and ϕ is the angle between $\Delta\vec{k} = \vec{k}_g - \vec{k}_r$ and the motional axis.

The scattering rate $W(\Delta_\pi)$ can be calculated from optical Bloch equations; see, for example, [12] for the three-level case. In Fig. 2 we plot the steady state vibrational excitation $\langle n(\infty)\rangle = \bar{n}$ calculated for our experimental system and for some idealized cases. The reduced efficiency in our system is due to the angle of 55° (rather than the ideal 90°) between the π polarized laser beam and the magnetic field. This restriction is imposed by the optical access to the trap and leads to a σ^- component that excites $|S,+\rangle \rightarrow |P,-\rangle$ transitions and leads to unwanted heating. In the calculations we have neglected the effect of the $P_{1/2} \rightarrow D_{3/2}$ transition because of the small branching ratio $(P_{1/2} \rightarrow D_{3/2})$:$(P_{1/2} \rightarrow S_{1/2})$ = 1:16.

The ion trap used in our experiment is the 1.4 mm sized 3D-quadrupole Paul trap, described in detail in [13]. For the experiments described below, a single $^{40}Ca^+$ ion is loaded into the trap, having oscillation frequencies $(\omega_x, \omega_y, \omega_z)/(2\pi)$ of (1.69, 1.62, 3.32) MHz. We investigated EIT cooling of the y and the z oscillation. The experiments proceed in three steps.

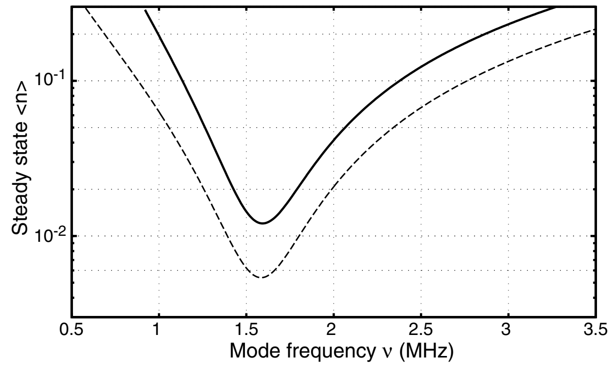

FIG. 2. Steady state vibrational excitation calculated for a three-level system (dashed line), which coincides with that for a four-level system and ideal polarizations, i.e., π light $\perp$ B field. The solid line shows the result for a four-level system with π light at 55° to the B field as in our experiment. Parameters are $\Delta_\sigma = \Delta_\pi = 2\pi \times 70$ MHz, $\Omega_\sigma = 2\pi \times 21.4$ MHz, and $\Omega_\pi = 2\pi \times 3$ MHz. The ac Stark shift is 1.6 MHz.

(i) We first Doppler precool the ion on the $S_{1/2}$ to $P_{1/2}$ transition at 397 nm (natural linewidth 20 MHz). The necessary UV light near 397 nm is generated by frequency doubling a Ti:sapphire laser. This light is passed through an acousto-optical modulator (AOM) driven at 80 MHz to switch the light for the different steps of our experiment. The +1st diffraction order beam is then focused and directed onto the ion. A detuning of approximately −20 MHz with respect to the $S_{1/2} \rightarrow P_{1/2}$ transition line is chosen for optimum Doppler cooling results. To avoid optical pumping into the $D_{3/2}$ states, we employ a grating stabilized diode laser near 866 nm [14]. The Doppler cooling limit on this transition of 0.5 mK corresponds to mean vibrational quantum numbers of $\bar{n}_z \approx 3$ and $\bar{n}_x \approx \bar{n}_y \approx 6$. The cooling limits reached in our experiment are higher, due to the fact that the simple assumption of a two-level system in the determination of the Doppler limit does not hold in our case. We experimentally determined the mean excitation numbers after Doppler cooling to be $\bar{n}_z = 6.5(1.0)$ and $\bar{n}_y = 16(2)$.

(ii) After Doppler cooling we apply a bichromatic pulse of radiation around 397 nm for EIT cooling that will be described in more detail below.

(iii) Finally we analyze the motional state after EIT cooling by spectroscopy on the $S_{1/2} \rightarrow D_{5/2}$ quadrupole transition at 729 nm. There we can resolve the motional sideband structure and detect the final electronic state with an electron shelving technique [13]. The quadrupole transition is excited with 729 nm radiation from a frequency stabilized Ti:sapphire laser with a bandwidth of $\delta\nu \leq 100$ Hz. A diode laser at 854 nm serves to repump the ion from the $D_{5/2}$ to the $S_{1/2}$ level.

In more detail, step (ii) is technically realized in the following way: To generate the two blue-detuned beams for EIT cooling we use the zero order beam out of the Doppler switch AOM, split it with a 50/50 beam splitter, pass the two emerging beams through another two AOMs at 86 MHz (cooling laser) and 92 MHz (coupling laser), respectively, and focus the +2nd diffraction orders onto the ion. The frequency difference equals the Zeeman splitting of the $|S, \pm\rangle$ levels in the quantization B field (4.4 G). By this arrangement, the Fano absorption profile for the cooling laser is created at approximately 75 MHz (about 3.5 natural linewidths) above the $|P, +\rangle$ level. The k vectors of the cooling beams enclose an angle of 125° and illuminate the ion in such a way that their difference $\Delta\vec{k}$ has a component along all trap axes $[(\phi_x, \phi_y, \phi_z) = (66°, 71°, 31°)$, where ϕ_i denotes the angle between $\Delta\vec{k}$ and the respective trap axis].

To roughly set the light intensity on the ion such that the ac Stark shift of the $|P, +\rangle$ level due to the σ^+ beam coincides with the trap frequency, we recorded spectra of the $S_{1/2} \rightarrow D_{5/2}$ quadrupole transition with the dressing σ^+ laser beam switched on. The σ^+ beam shifts the $|S, -\rangle$ level by an amount that is equal in magnitude to the ac Stark shift of the dressed $|P, +\rangle$ level used in the cooling scheme. Therefore by determining the change in the carrier $|S, -\rangle \rightarrow D_{5/2}(m = -5/2)$ transition frequency versus the σ^+ intensity we obtained a direct measure of the ac Stark shift relevant for EIT cooling [15].

Then we applied EIT cooling to the radial y mode of our trap with a frequency of $\omega_y = 2\pi \times 1.62$ MHz. After 1.5 ms of Doppler cooling, we switched on both EIT cooling beams for 7.9 ms. The σ^+ beam was left on for 50 μs after the π beam was turned off to optically pump the ion to the $|S, +\rangle$ ground state. We then monitored the final state by exciting Rabi oscillations on the blue sideband of the $|S, +\rangle \rightarrow D_{5/2}(m = +5/2)$ transition and measuring the $|S, +\rangle$ level occupation as a function of the pulse length [13]. The Rabi oscillations were subsequently fitted to determine the mean vibrational occupation number $\bar{n}_y$ [16]. We recorded $\bar{n}_y$ as a function of the ac Stark shift δ by varying the intensity of the σ^+ beam around the value $\delta = \omega_y$ previously determined. Our results are depicted in Fig. 3, showing that the initial thermal distribution with $\bar{n}_y = 16$ is cooled close to the ground state over a wide range of ac Stark shifts. As expected the most efficient cooling occurs for $\delta \simeq \omega_y$ [17].

The lowest mean vibrational number $\bar{n}_y = 0.18$ observed for $\delta = 2\pi \times 1.6$ MHz corresponds to 84% ground state probability. We repeated this experiment on the 3.3 MHz z mode after having increased the intensity of the σ^+ beam. For this mode, a minimum mean vibrational number of $\bar{n}_z = 0.1$ was obtained, corresponding to 90% ground state probability for $\delta = 2\pi \times 3.3$ MHz.

The cooling results are largely independent of the intensity of the π beam as long as it is much smaller than the σ^+ intensity. In our experiment the intensity ratio was $I_\sigma/I_\pi \simeq 100$ and we varied the intensity of the π beam by a factor of 4, with no observable effect on the final $\bar{n}$.

By determining the dependence of the mean vibrational quantum number on the EIT cooling pulse length τ, we measured the cooling time constant to be 250 μs; see Fig. 4.

In order to show that the EIT method is suitable to simultaneously cool several vibrational modes with vastly different frequencies of oscillation, we chose the axial z mode at 3.3 MHz, and the radial y mode at 1.62 MHz, which have a frequency difference of 1.7 MHz. The intensity of the σ^+ beam was set such that the ac Stark shift was 2.6 MHz, roughly halfway between the two mode frequencies. Again we applied the EIT cooling beams for 7.9 ms after Doppler cooling. This time we determined the final $\bar{n}$ by comparing the excitation probability on the red and the blue sideband of the $S_{1/2}(m = 1/2) \rightarrow D_{5/2}(m = 5/2)$ transition [5]. We find both modes cooled deeply inside the Lamb-Dicke regime ($\eta\sqrt{\bar{n}} \ll 1$), with $p_0^{(y)} = 58\%$ and $p_0^{(z)} = 74\%$ ground state probability.

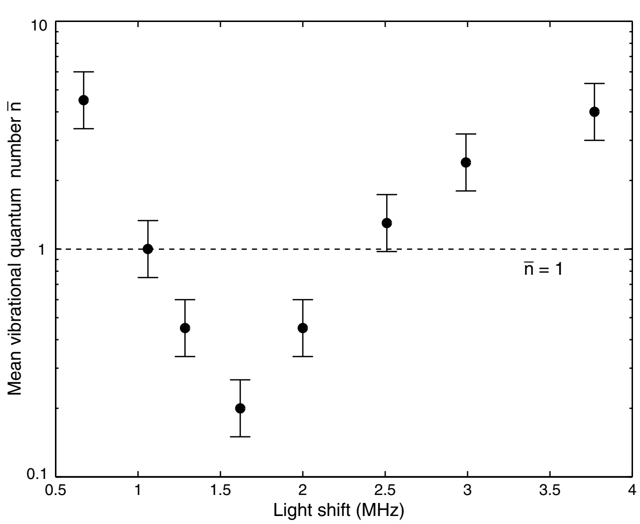

FIG. 3. Mean vibrational quantum number $\bar{n}_y$ vs ac Stark shift $\delta/2\pi$, after 7.9 ms of EIT cooling (starting from a thermal distribution with $\bar{n}_y = 16$).

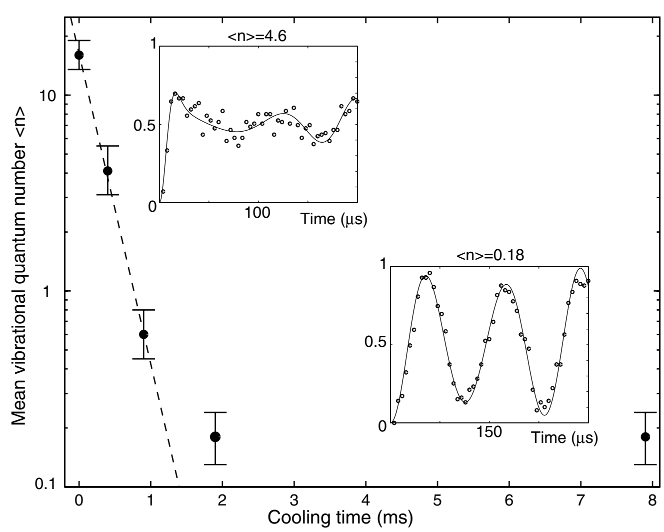

FIG. 4. Mean vibrational quantum number $\bar{n}_y$ vs EIT cooling pulse length τ. The insets show Rabi oscillations excited on the upper motional sideband of the $|S, +\rangle \rightarrow D_{5/2}(m = +5/2)$ transition, after 0.4 ms (left) and 7.9 ms (right) of EIT cooling. A thermal distribution is fitted to the data to determine $\bar{n}_y$.

In conclusion we have experimentally demonstrated a novel cooling method for trapped particles which allowed us to efficiently cool a trapped ion to the ground state of motion, using only a Zeeman-split dipole transition. We also showed that the cooling mechanism has a considerable bandwidth and should thus allow us to simultaneously cool several modes of longitudinal ion motion in a linear trap. This is important for implementing quantum logical gates with trapped ions, because the requirement of individual optical addressing puts an upper limit on the motional frequencies that usually makes it desirable to cool these modes below the Doppler limit. The cooling method does not require a forbidden transition and involves a lower technical overhead as compared to other ground state cooling methods demonstrated so far. Furthermore, the demonstrated method is not restricted to trapped ions and should work for trapped neutral particles as well. Its large bandwidth should make this scheme especially attractive for optical lattices since the slight anharmonicity and site-to-site inhomogeneity of the lattice potentials does not hinder effective cooling.

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