Ground-state cooling of a trapped ion using long-wavelength radiation

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We demonstrate ground-state cooling of a trapped ion using long-wavelength radiation. This is a powerful tool for the implementation of quantum operations, where long-wavelength radiation instead of lasers is used for motional quantum state engineering. We measure a mean phonon number of $\bar{n} = 0.13(4)$ after sideband cooling, corresponding to a ground-state occupation probability of 88(7)%. After preparing in the vibrational Fock state $|n = 0\rangle$, we implement sideband Rabi oscillations which last for more than 10 ms, demonstrating the long coherence time of our system. We also use the ability to ground-state cool to accurately measure the motional heating rate and report a reduction by almost two orders of magnitude compared to our previously measured result, which we attribute to carefully eliminating sources of electrical noise in the system.

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Trapped atomic ions are a well established platform for the implementation of quantum computation [1-2], quantum simulation [3-4] and frequency standards experiments [5]. Realising such experiments often requires cooling the ions to below the Doppler limit. A very successful technique to achieve this is resolved sideband laser cooling, which was first implemented and used to reach the ground-state of motion in seminal experiments on a quadrupole transition using a very narrow-linewidth laser [6] and on a Raman transition [7]. Further refinement of the technique has lead to a motional ground-state occupation probability of 99.9% [8].

While the initial seminal examples of quantum state engineering and sub-Doppler cooling were performed using laser radiation, in recent years exciting new schemes for the creation of the required coupling between the internal state of an ion and its harmonic motion have been proposed in the pioneering work by Mintert and Wunderlich [9] and Ospelkaus et al. [10] in which long-wavelength radiation is used instead. The successful demonstration of quantum operations such as high-fidelity single and multi-qubit gates as well as cooling to below the Doppler laser cooling limit to reach the ground-state of motion using long-wavelength radiation is expected to provide a powerful platform for scaling up a broad range of quantum technologies. Following the initial proposals, the first two-qubit gate using long-wavelength radiation was implemented using near-field microwave gradients [11] which was followed by the implementation of a two-qubit gate between nearest as well as non-nearest neighbours using microwaves in conjunction with a static magnetic field gradient [12]. More recently long-wavelength radiation has also been used to perform single-qubit gates with a fidelity far exceeding the minimum threshold for fault-tolerant quantum computing [13].

Cooling an ion to the quantum ground-state of motion using long-wave radiation would be highly desirable as it would constitute a powerful toolset for quantum state engineering experiments [14-20]. So far, near-field microwave gradients have been used to sideband cool a cold high frequency radial mode to a mean phonon number of $\bar{n} = 0.6(1)$ [11] and microwaves in conjunction with a static magnetic field gradient were used to sideband cool a lower frequency axial mode to $\bar{n} = 23(7)$ [12]. The successful cooling to the ground-state of motion using long-wavelength radiation, however, remains a significant challenge.

In this manuscript we demonstrate ground-state cooling of a $^{171}$Yb$^+$ ion using a strong radio-frequency (RF) field in conjunction with a large static magnetic field gradient. Laser radiation is used only for initial Doppler cooling and optical pumping for preparation of the ion’s internal state and additional microwave fields are used to dress the ion, increasing ionic coherence times. Following sideband cooling we measure a final phonon number of $\bar{n} = 0.13(4)$ which corresponds to a ground-state population probability of 88(7)%. We combine the ability to prepare the vibrational Fock state $|n = 0\rangle$ with the significant increase in coherence time of our dressed system to observe sideband Rabi oscillations which last for more than 10 ms and use our ground-state cooling method to measure the motional heating rate of our ion trap.

A segmented macroscopic linear Paul trap with an ion-electrode distance of 310 µm is used to confine a single $^{171}$Yb$^+$ ion [21]. Once the ion is trapped it is Doppler laser cooled on the $^2S_{1/2} \leftrightarrow ^2P_{1/2}$ transition using near-resonant 369 nm light. To form a closed cooling cycle any population in the $^2D_{3/2}$ state is transferred to the $^3S_{1/2}$ state using resonant light at 935 nm from which the population decays back to the $^2S_{1/2}$ state. By tuning the 369 nm light to be resonant with the $^2S_{1/2}$, F=1 $\leftrightarrow$ $^2P_{1/2}$, F=1 transition, the $|0\rangle = ^2S_{1/2} |F = 0\rangle$ state is prepared with near unit fidelity in < 10 µs. State detection is achieved using a fluorescence threshold technique whereby light is tuned to be resonant with the $^2S_{1/2}$, F=1 $\leftrightarrow$ $^2P_{1/2}$, F=0 cycling transition [22].
In order to obtain a coupling between the motion of the ion and long-wavelength radiation, we apply a large static magnetic field gradient to the ion using four permanent rare earth SmCo magnets integrated close to the ion trap. The static magnetic field gradient has been measured to be 23.6(3) T/m [21]. By driving transitions within the ground-state with \( \Delta n_F = \pm 1 \) using long-wavelength radiation a coupling strength is obtained which scales with an effective Lamb-Dicke parameter (LDP) \( \eta_{\text{eff}} = z_0 \mu_B \nabla_B / h \nu_z \). Here \( \nabla_B \) is the static magnetic field gradient, \( \nu_z \) is the axial secular frequency, \( \mu_B \) is the Bohr magneton and \( z_0 = \sqrt{\hbar / 2m \nu_z} \) is the spatial extent of the ground-state wave function. For a measured axial secular frequency of \( \nu_z / 2\pi = 426.7(1) \) kHz, which is used in this work, we obtain \( \eta_{\text{eff}} = 0.0064 \). The ion is slightly displaced from the magnetic field nil to give a magnetic field offset at the ion of 10.5 G which lifts the degeneracy of the \( ^2S_{1/2} \), \( F=1 \) Zeeman-levels \( |0\rangle = ^2S_{1/2} [F = 1, m_F = 0] \), \(|+1\rangle = ^2S_{1/2} [F = 1, m_F = +1] \) and \( |-1\rangle = ^2S_{1/2} [F = 1, m_F = -1] \) by \( \approx 14.6 \) MHz and results in a second-order Zeeman shift which separates the \(|0\rangle \leftrightarrow |+1\rangle \) transition and the \(|0\rangle \leftrightarrow |-1\rangle \) transition by 34 kHz [22].

The requirement to use states with different magnetic moments for spin-motion coupling with a static magnetic field gradient limits the coherence time, as the system is sensitive to ambient magnetic field fluctuations [12, 21].

The coherence time of our bare magnetic field sensitive system is \( \approx 1 \) ms which is on the same order of magnitude as the ground-state sideband \( \pi \)-time used in our experiment and therefore limits the efficiency of the cooling process. To significantly increase the coherence time of our system, we apply a pair of dressing fields using microwaves near 12.6 GHz to the ion which resonantly couple the magnetic field sensitive states \(|+1\rangle \) and \(|-1\rangle \) with the first-order magnetic field insensitive state \(|0\rangle \) with equal Rabi frequency \( \Omega_{\text{dr}} \) [22,24]. This gives three dressed-states, one of which \(|D\rangle = (|+1\rangle - |-1\rangle)/\sqrt{2} \) can be combined with \(|0\rangle \) to form an effective two-level system that is resilient to noise in the magnetic field [22,24].

Preparation and detection of the dressed-state system is achieved using the method described in Ref. [24]. For preparation, a microwave \( \pi \)-pulse transfers the population to \(|0\rangle \) after the ion has been optically pumped into the \(|0\rangle \) state. The microwave dressing fields are then applied instantaneously, after which an RF field resonant with the \(|0\rangle \leftrightarrow |+1\rangle \) transition is used to couple \(|0\rangle \) and \(|D\rangle \) [22,24]. Detuning the RF field either side of the carrier transition by the motional trap frequency then allows the coupling to motional sideband transitions, analogous to an undressed two-level system, however also resilient to magnetic field fluctuations. To detect the final state, the dressing fields are turned off, after which a microwave \( \pi \)-pulse swaps population between \(|0\rangle \) and \(|0\rangle \). The fluorescence threshold detection technique can now be used to distinguish between population in \( ^2S_{1/2}, F=1 \) and \(|0\rangle \), corresponding to the effective two-level system \(|D\rangle \) (absent any decoherence during the dressing) and \(|0\rangle \) respectively.

The motional ground state \(|n=0\rangle \) is prepared using a pulsed sideband cooling technique [7] which we implement as follows: After a period of Doppler laser cooling using near resonant 369 nm light, the ion is initialised in \(|0\rangle \) and the dressing fields are turned on. An RF field resonant with the red sideband transition, detuned from the carrier transition \(|0\rangle \leftrightarrow |D\rangle \) by the secular frequency \( \nu_z \), is then applied for a time \( t \). The probability to make a transition from \(|0\rangle \) to \(|D\rangle \) for a resonant sideband transition is given by

\[
P_{n,n\pm1}(t) = \sum_{n=0}^{\infty} p_n \frac{1}{2} (1 - \cos(\Omega_{n,n\pm1} t)),
\]

where the \( +(-) \) sign is used for a blue (red) sideband transition respectively. Here \( p_n \) is the population in the \( n \)th motional state and, to first-order in \( \eta_{\text{eff}} \), \( \Omega_{n,n-1} = \eta_{\text{eff}} \Omega \sqrt{n} \) is the Rabi frequency for the \(|0\rangle, n \leftrightarrow |D, n-1 \rangle \) transition, while \( \Omega_{n,n+1} = \eta_{\text{eff}} \Omega \sqrt{n+1} \) is the Rabi frequency for the \(|0\rangle, n+1 \leftrightarrow |D, n \rangle \) transition. \( \Omega \) is the carrier Rabi frequency and for an ion in a thermal distribution of motional states characterised by a mean phonon number \( \bar{n} \), the motional state populations are given by \( p_n = (1/(\bar{n}+1))/(\bar{n} /(\bar{n} + 1))^{n} \). After the RF pulse, the dressing fields are turned off and a resonant microwave \( \pi \)-pulse swaps population between \(|0\rangle \) and \(|0\rangle \) to minimise heating due to photon scattering during realisation.
Any population in the $^2S_{1/2}$, F=1 manifold is then repumped into $|0\rangle$ using 369 nm light. This sideband cooling sequence is repeated until the ion’s motional state arrives at $|n = 0\rangle$.

To measure the final motional state after sideband cooling, an RF probe pulse is applied after preparing in $|0\rangle$ and applying the dressing fields. The frequency of the RF field is scanned over both the red and blue sideband. The ratio of probabilities to make a transition from $|0\rangle$ to $|D\rangle$ when resonant with the red or blue sideband can be shown from Eq. 1 to be $r = P_{n,n-1}(t)/P_{n,n+1}(t) = \bar{n}/(\bar{n} + 1)$, assuming the ion is in a thermal state. This ratio can therefore be used to extract the final $\bar{n}$.

Before sideband cooling, we measure the population in $^2S_{1/2}$, F=1 as a function of the time that we resonantly drive the red sideband transition for and fit the resultant data using Eq. 1 to extract the initial temperature after 4 ms of Doppler cooling, which was found to be $\bar{n} = 65(5)$. This method is chosen to measure the initial temperature as no observable difference between the red and blue sideband transition probabilities is observable at such large value of $\bar{n}$.

Following 4 ms of Doppler cooling to $\bar{n} = 65(5)$ and 10 $\mu$s of optically pumping into $|0\rangle$ the sideband cooling sequence method explained above is experimentally implemented as follows. A resonant 14 $\mu$s microwave $\pi$-pulse swaps population between $|0\rangle$ and $|0'\rangle$ for preparation and detection of the dressed-state system and the Rabi frequencies of the two dressing fields have been independently measured to be $\Omega_{d}/2\pi = 32$ kHz. The sideband cooling RF field with a carrier Rabi frequency of $\Omega/2\pi = 61.2$ kHz is set on resonance with the red sideband of motion which is separated from the carrier by the axial secular frequency $\nu_{z}/2\pi = 426.7(1)$ kHz and applied to the ion for a time $t$. The optical re-pumping into $|0\rangle$ is applied for 6 $\mu$s. We apply a total of 500 repetitions of the sideband cooling sequence, where for each repetition the RF sideband pulse is applied for an increasing length of time. The sideband pulse times are set to be $t_n = \pi / \Omega_{n,n-1}$ for each $n$ level in turn, starting from $n = 500$, giving a total sideband cooling time of 71 ms. After the sideband cooling sequence the frequency of the RF probe field is scanned over the red and blue sidebands with a pulse time of 1270 $\mu$s. The result of this scan is shown in Fig. 3 (a) and (b) for the red and blue sideband respectively. From this we extract a final mean phonon number of $\bar{n} = 0.13(4)$, corresponding to a ground-state occupation probability of $p_0 = 0.88(7)$. This result is consistent with the minimum temperature estimated when taking into account effects from heating.

A limiting factor of the maximum achievable ground-state population probability is the heating rate of the motional mode being cooled. The heating rate of an ion in our trap has previously been measured and a scaled spectral noise density of $\nu_{z} S_{\nu_{z}}(\nu_{z}) = 4\hbar h m \nu_{z}^{2}/\epsilon^2 = 2.3(6)\times10^{-4}$ V$^2$m$^{-2}$ has been calculated [24]. This would correspond to a heating rate of 6738 $s^{-1}$ at a secular frequency of $\nu_{z}/2\pi = 426.7(1)$ kHz. Methods to significantly reduce the heating rate include cooling of the trap electrodes [26] and the use of a sputter gun [27] or a high intensity pulsed-laser [28] to clean the surface of the trap. These methods are useful if no other dominating sources of heating are present. Electrical noise in the laboratory has long been thought of as being a potentially dominating source of heating in many heating rate measurements [29][30]. We have carefully detected and reduced sources of electromagnetic noise in the vicinity of the experiment. This includes replacing noise-inducing electronics as well as using a well separated ground for relevant low-noise electronics. We have also developed a
new low noise multi-channel voltage supply for the static voltage trap electrodes which is connected to a custom filter box featuring a 4th order low pass RC filter with a cut-off frequency of 32 Hz, a total DC resistance of 4 kΩ and 14 capacitors per channel ranging from 2 µF to 390 pF to cover a broad frequency range of noise. We have also built a Faraday cage around the vacuum system.

To measure the new heating rate of the ion we modify the sideband cooling sequence described above to include a variable delay time. The delay is inserted after the sideband cooling but before the RF probe pulse, during which the ion heats at a rate $\dot{\bar{n}}$. By performing the experiment for delay times of 0 ms, 5 ms and 10 ms, a heating rate can be extracted. The measured temperature for each delay time is shown in Fig. 2. A fit to the data gives a heating rate of $41(7) \text{ s}^{-1}$, which corresponds to a gain of 1 phonon every 24 ms. This heating rate gives a scaled electric-field noise density of $\nu_0 S_E(\nu_0) = 1.4(2) \times 10^{-6}$ V²m⁻², which is a reduction of more than two orders of magnitude compared to our previously measured value and reiterates the importance of carefully controlling electrical noise present in the laboratory.

The ability to ground-state cool in conjunction with the long coherence time offered by our dressed-system allows us to investigate the coherence properties of the ion’s motional state. To demonstrate this we sideband cool the axial mode of motion using the method described above and prepare the Fock state $\ket{n = 0}$. We then apply a RF field resonant with the blue sideband of motion ($(0', n = 0) \leftrightarrow |D, n = 1 \rangle$) for an increasing time, resulting in Rabi oscillations with frequency $\eta_{\text{eff}} \Omega/2\pi = 0.35$ kHz, coherently manipulating the phonon state. This is shown in Fig. 3 and demonstrates that Rabi oscillations are maintained for over 10 ms, an order of magnitude longer than achievable two-qubit gate times currently envisioned to be implemented in this system. We also apply a RF field resonant with the red sideband for an increasing time in a separate experiment, which is also shown in Fig. 3. A theoretical line for both sets of data is overlaid, which is the result of numerically integrating a master equation incorporating the effect of heating. It can be seen that using the measured heating rate, the data closely matches the simulated curves.

We have experimentally demonstrated ground-state cooling of an ion by coupling an effective two-level microwave-dressed system to its motion using long-wavelength radiation in conjunction with a large static magnetic field gradient. We also show coherent manipulation of the motional state, by demonstrating multiple Rabi oscillations on the blue sideband which corresponds to the repeated exchanges of excitation between the internal and motional states of the ion. Furthermore, we have measured a reduction of the motional heating rate of the ion by almost two-orders of magnitude, which we attribute to careful minimisation of external electric field noise. By demonstrating ground-state cooling using long-wavelength radiation to drive the sideband transitions, we complete a toolbox of techniques for quantum state engineering using long-wavelength radiation. Laser radiation is used only for detection, Doppler cooling and optical pumping, removing the need for highly stable laser sources or multiple laser beams in a Raman configuration. This simplification significantly reduces the experimental resources required for scaling quantum engineering techniques to a large number of ions.

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