Adiabatic cooling of a single trapped ion

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We present experimental results on adiabatic cooling of a single \(^{40}\text{Ca}^+\) ion in a linear radiofrequency trap. After a period of laser cooling, the secular frequency along the rf-field-free axis is adiabatically lowered by nearly a factor of eight from \(\nu_z = 583\) kHz to \(\nu_z = 75\) kHz. For an ion originally Doppler laser cooled to a temperature of \(0.65 \pm 0.03\) mK, a temperature of \(87 \pm 7\) µK is measured after the adiabatic expansion. Applying the same adiabatic cooling procedure to a single sideband cooled ion in the ground state \((P_0 = 0.978 \pm 0.002)\) resulted in a final ground state occupation of \(0.947 \pm 0.005\). Both results are in excellent agreement with an essentially fully adiabatic behavior. The results have a wide range of perspectives within such diverse fields as ion based quantum information science, high resolution molecular ion spectroscopy and ion chemistry at ultra-low temperatures.

Cooling through adiabatic expansion is a general and well-known method to reduce the temperature of a gaseous system. For instance, within cold atomic gas physics, adiabatic cooling has previously been demonstrated with neutral atoms by applying optical lattices \([1,2]\). Here, one of the most spectacular results has been the possibility to study the transition from the MOT insulating to the superconducting phase of ultracold atoms \([3]\). Adiabatic cooling of trapped ions was discussed several decades ago \([4,5]\), while only recently adiabatic cooling played a major role in reaching the lowest temperatures for ensembles of antiprotons ever \([6]\). So far, pure adiabatic cooling of a single trapped ion has not yet been investigated experimentally.

For ion based quantum information science, adiabatic motional dynamics has so far mainly been a concern in connection with experiments on shuttling \([7,8]\) and separating of ions \([9]\), but for ion quantum logic gates based on magnetic field gradients \([10,11]\), separation of ions through adiabatic opening of the trap potential could be an advantage. Furthermore, adiabatic cooling could possibly become a vital tool for both high resolution molecular ion spectroscopy \([12-17]\) and ultracold ion chemistry \([18,19]\). With respect to the first topic, the possibility to reach low ion oscillation frequencies while staying in the motional ground state may open up for quantum logic spectroscopy \([20]\) on rather long wavelength vibrational transitions; e.g., for testing fundamental physics \([14-17]\). For the latter topic, adiabatic cooling could make it possible to enter the ultracold regime (µK and below) where new chemistry is expected \([21,22]\).

In this paper, we present a detailed investigation of adiabatic cooling a single \(^{40}\text{Ca}^+\) ion in a linear rf quadrupole trap. Through adiabatic lowering of the secular frequency along the rf free axis from a value of \(\nu_z = 583\) kHz down to \(\nu_z = 75\) kHz, we demonstrate cooling from Doppler cooled conditions \((T = 0.69 \pm 0.02\) mK) down to \(T = 87 \pm 7\) µK - equivalent to a temperature six times lower than the theoretic Doppler limit \((T = 0.5\) mK).

For the same adiabatic procedure, we furthermore show that an ion sideband cooled to the ground state \((P_0 = 0.978 \pm 0.002)\) can be kept in this state with a probability above 97%.

The setup and procedures used are the same as described in Ref. \([23]\) except for the sideband cooling step. In the current work, sideband cooling is realized by a continuous scheme where the ion is addressed simultaneously by light at 729 nm and 854 nm. The light at 729 nm excites the ion on the red sidebands of the \(S_{1/2}(m_J = -1/2)\leftrightarrow D_{5/2}(m_J = -5/2)\) transition while the 854 nm light acts to broaden the upper level by coupling it to the ground state via excitation to the higher lying \(P_{3/2}\) level. The sideband cooling starts with 0.5 ms cooling on the 2nd red sideband followed by 0.5 ms cooling on the first red sideband with optical power corresponding to Rabi frequencies in the range of few hundreds of kHz. This power provides fast cooling but at the cost of significant off resonant excitation. To reach the ground state with high probability, the cooling sequence is finalized by a low power step with a Rabi frequency around 30 kHz lasting 5 ms. During all cooling steps, the 729nm light is additionally switched to the \(S_{1/2}(m_J = +1/2)\leftrightarrow D_{5/2}(m_J = -1/2)\) transition every 100 µs to avoid trapping in the \(S_{1/2}(m_J = +1/2)\) state.

After a period with laser cooling (5 ms Doppler cooling optionally followed by 6 ms of sideband cooling) at the high secular frequency, the laser light is switched off and the axially confining dc potential applied to the eight end-electrodes is lowered through a filtering circuit (used to combine the rf and dc potentials) with a characteristic time constant of 1 ms. A 5 ms delay is inserted before starting the measurements of the motional state of the ion to assure the axial trap potential has settled. The rather long ramp time safely situates the experiments at all time within the adiabatic regime set by \(\nu_z/\nu_z^2 \ll 2\pi\), where \(\nu_z\) is the relevant secular frequency. At the few millisecond time scale, serious problems concerning spurious heating of the ion is not expected since we have
FIG. 1. Sideband spectra before and after adiabatic lowering of the secular frequency along the rf field free axis. (a) Excitation probabilities for the carrier and the first four sidebands after Doppler cooling including best fits for a thermal motional distribution. The horizontal axis indicates the detunings with respect to the sideband frequencies $n \cdot \nu_z$ ($\nu_z = 583$ kHz). (b) Expected sideband excitation probabilities versus temperature for a thermal motional distribution. The vertical bars indicates the height of the various sidebands and the width the standard deviation extracted from the fit. The vertical axis is the same as in (a). (c) As (a) but after adiabatically opening the trap potential ($\nu_z = 75$ kHz). (d) As (b) after lowering secular frequency ($\nu_z = 75$ kHz).

consistently measured heating rates of one vibrational quanta per second in the frequency range 280 - 585 kHz [23].

For the Doppler cooling experiments, the initial and final temperature is derived by comparing the excitation spectrum spanning the carrier and four lowest order red sidebands with those expected assuming a thermal distribution. In Fig. 1, such spectra are presented both before (a), and after (c), the adiabatic cooling. To extract the temperature, the excitation probabilities for the sidebands are matched to a thermal model as illustrated in (b) and (c). Clearly, the excitation matches the model well and suggests initial and final temperatures of $0.65 \pm 0.03$ mK and $87 \pm 7$ $\mu$K respectively. The ratio of these temperatures match that of the secular frequencies, 7.8, within the uncertainties indicating good adiabatic behavior.

In the sideband cooled case, the ground state population is deduced by comparing the excitation probabilities when addressing the first red and blue sidebands [24]. In Fig. 2, these spectra are presented (a) before, and (b) after, the adiabatic cooling process. Fig. 2 suggests a ground state population of $97.8 \pm 0.2\%$, while from Fig. 2b, a value of $94.7 \pm 0.5\%$ can be inferred. Again, a near perfect adiabatic cooling has been achieved, though with indication of minor heating. The final state distribution corresponds to a translational temperature of $\sim 1.3 \mu$K.

In conclusion, we have demonstrated very effective adiabatic cooling of an ion cooled either initially to near the Doppler limit or to its ground state of motion. In both cases, essentially perfect adiabatic cooling has been achieved. The demonstrated adiabatic cooling will likely find applications within a wide range of ion based re-
search, including quantum information science, high resolution molecular ion spectroscopy and ultracold ion chemistry.

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