GROUND STATE LASER COOLING OF TRAPPED ATOMS USING ELECTROMAGNETICALLY INDUCED TRANSPARENCY

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A laser cooling method for trapped atoms is presented which achieves ground state cooling by exploiting quantum interference in a Λ-shaped arrangement of atomic levels driven by two lasers.[1] The scheme is technically simpler than existing methods of sideband cooling, yet it can be significantly more efficient, in particular when several motional modes are involved. We have applied the method to a single Calcium ion in a Paul trap,[2] coupling a single laser to the Zeeman structure of its $S_{1/2} \to P_{1/2}$ dipole transition at 397 nm. We have achieved more than 90% ground-state occupation probability. By suitably tuning the laser parameters, we obtain simultaneous ground-state cooling of two oscillator modes. This is of great practical importance for the implementation of quantum logic schemes with trapped ions.

The cooling method. We consider three atomic levels, $|g\rangle$ (ground), $|e\rangle$ (excited), and $|r\rangle$ (metastable), arranged in a Λ-scheme and laser-excited as in Fig. 1a. The transition $|r\rangle \to |e\rangle$ is strongly driven by a blue-detuned laser (coupling laser) with Rabi frequency Ω_r and detuning Δ_r. The absorption spectrum of a probe (cooling) laser driving the transition $|g\rangle \to |e\rangle$ at detuning Δ_g shows a zero at $\Delta_g = \Delta_r$ (dark resonance, EIT-condition), a narrow resonance at $\Delta_g = \Delta_r + \delta$, and a broad resonance at $\Delta_g = -\delta$, where $\delta = (\sqrt{\Delta_r^2 + \Omega_r^2} - |\Delta_r|)/2$ is the light shift due to the coupling laser (inset in Fig. 1a).

We assume that the atomic center-of-mass motion is harmonic at frequency ν and that the Lamb-Dicke regime holds, i.e. the size of the motional state is much smaller than the laser wavelength. Let $|n\rangle$, $n = 0, 1, 2, \ldots$, be the energy eigenstates of the motion. The probe absorption spectrum can then be decomposed into transitions between different motional states, of which the significant contributions are the $|n\rangle \to |n\rangle$ "carrier" transition at Δ_g and the $|n\rangle \to |n \pm 1\rangle$ "sideband" transitions at $\Delta_g \mp \nu$. By tuning the probe laser to $\Delta_g = \Delta_r$, the absorption probability on these transitions is such that: (i) Carrier absorption is suppressed, since it corresponds to the dark resonance

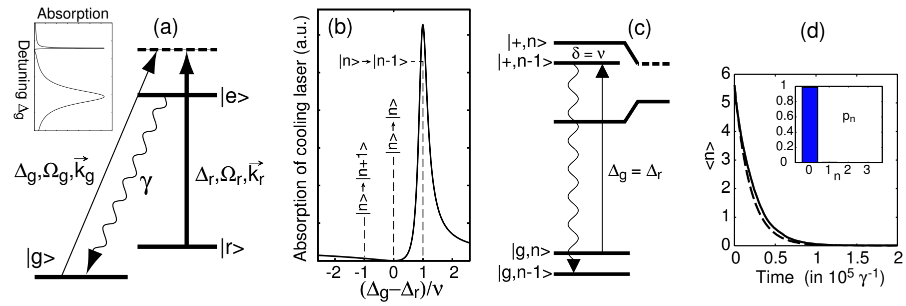

Figure 1. (a) Levels and transitions of the EIT-cooling scheme. The inset shows schematically the absorption rate on $|g\rangle \to |e\rangle$ when the atom is strongly excited above resonance on $|r\rangle \to |e\rangle$. (b) Absorption of cooling laser around $\Delta_g = \Delta_r$ (solid line); dashed lines mark the probabilities of carrier ($|n\rangle \to |n\rangle$) and sideband ($|n\rangle \to |n \pm 1\rangle$) transitions when $\Delta_g = \Delta_r$. (c) Dressed state picture: the cooling laser excites resonantly transitions from $|g, n\rangle$ to the narrow dressed state denoted by $|+, n-1\rangle$ which preferentially decays into $|g, n-1\rangle$. (d) Quantum Monte-Carlo simulation of the cooling dynamics (solid line) and rate equation approximation (dashed line), calculated with $\Omega_r = \gamma$, $\Delta_r = 2.5\gamma$ and $\nu = \gamma/10$. The inset shows the population of the lowest vibrational states after cooling (from Ref. [1]).

(EIT); (ii) blue-sideband absorption ($|n\rangle \to |n+1\rangle$) has very small probability, falling on the left of the dark resonance, while (iii) red-sideband absorption ($|n\rangle \to |n-1\rangle$) is strongly enhanced, and it is maximum when the condition $\delta \simeq \nu$ holds (Fig. 1b). This is the principle of EIT cooling. Note that, in absence of the coupling laser, the dipole transition of width $\gamma \gg \nu$ would only permit Doppler cooling.

The procedure can also be understood as optical pumping between $|g\rangle$ and the dressed states of the driven $|r\rangle \to |e\rangle$ transition, see Fig. 1c. While this picture looks similar to ordinary sideband cooling, EIT cooling can in fact provide *higher* efficiency, in particular for cooling in 3 dimensions.[1] This is a result of the total suppression of the carrier transition $|g, n\rangle \to |+, n\rangle$ due to the EIT condition. In Fig. 1d the cooling efficiency is evaluated numerically, showing that near-unity occupation of the ground state is achieved.

Experimental realization. The scheme has been applied to a single $^{40}\mathrm{Ca}^+$ ion trapped in a Paul trap, whose $\mathrm{S}_{1/2} \leftrightarrow \mathrm{P}_{1/2}$ dipole transition at 397 nm forms a four-level system (Fig. 2a). Three of the levels, $|S, \pm\rangle$ and $|P, +\rangle$, together with the σ^+ and π-polarized laser beams, form the Λ scheme (Fig. 2b). The ion is stored in a trap with $(\nu_x, \nu_y, \nu_z) = 2\pi \times (1.69, 1.62, 3.32)$ MHz and first Doppler cooled on $\mathrm{S}_{1/2} \to \mathrm{P}_{1/2}$ to mean excitation numbers $\bar{n}_z = 6.5(1.0)$ and $\bar{n}_y = 16(2)$. Then, EIT-cooling is applied with a pulse of σ^+- and π-light,

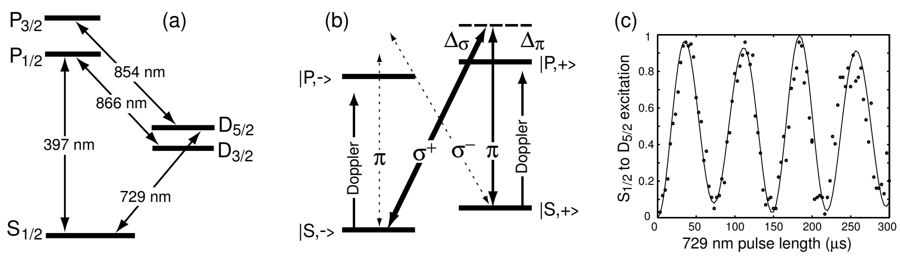

Figure 2. (a) Levels and transitions in $^{40}Ca^+$ used in the experiment. The $S_{1/2}$ to $P_{1/2}$ transition is used for Doppler cooling and for EIT-cooling, and the scattered photons are observed to detect the ion's quantum state. The narrow $S_{1/2} \rightarrow D_{5/2}$ transition serves to investigate the vibrational state. (b) Zeeman sublevels $|S, \pm\rangle$, $|P, \pm\rangle$ of $S_{1/2}$ and $P_{1/2}$, respectively, and laser frequencies (solid lines) which are relevant for EIT-cooling. Dashed lines: transitions which involve the $|P, -\rangle$ level. Due to a non-ideal polarization of the π-light the σ^--transition slightly counteracts the cooling. (c) Rabi oscillations excited on the blue z-mode sideband of the $S_{1/2} \leftrightarrow D_{5/2}$ transition (points). A mean phonon number of $\bar{n}_z = 0.1$ was determined from the fit (line).

blue-detuned to $\Delta_\sigma = \Delta_\pi \approx 75$ MHz (3.5γ) and with $\Omega_\sigma = 2\pi \times 21.4$ MHz and $\Omega_\pi = 2\pi \times 3$ MHz.[2] The motional state after cooling is analyzed by spectroscopy on the $S_{1/2} \rightarrow D_{5/2}$ quadrupole transition at 729 nm, using an electron shelving technique[3] (Fig. 2c). For $\delta = 2\pi \times 3.3$ MHz, a mean vibrational number of $\bar{n}_z = 0.1$ was obtained, corresponding to 90% occupation of the ground state of the axial motion.

The particular shape of the absorption spectrum (Fig. 1b) allows to simultaneously cool all modes whose frequencies lie around the value of the chosen δ. We have simultaneously cooled the z- and y-modes by setting Ω_σ such that $\delta \approx 2.6$ MHz, roughly halfway between the mode frequencies. Repeating the procedure outlined above, the modes were found to be cooled to $p_0^y = 58\%$ and $p_0^z = 73\%$ ground state probability (Fig. 4).

These results could be extended to cooling the motion of ion strings in linear ion traps. Here, the collective motion is described by the normal modes of the crystals. EIT-cooling seems to be particularly suited for cooling these modes, since it allows simultaneous cooling of several modes at different frequencies. We have estimated the cooling performance for a 10-ion string,[4] finding that all vibrational modes may be cooled to a mean phonon number below one. This is promising for the application of the procedure to cold ion strings for quantum information processing.

Finally, EIT-cooling is not restricted to harmonic motion: particles in anharmonic potentials can also be efficiently cooled, provided that the motional sideband frequencies are not too different from the light shift δ. For

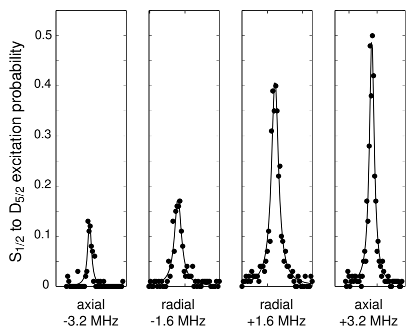

Figure 3. EIT-cooling of two modes at 1.6 MHz and 3.2 MHz simultaneously. From the sideband excitation rate after cooling we deduce a ground state occupation number of 73% for the axial mode (3.2 MHz) and 58% for the radial mode (1.6 MHz).

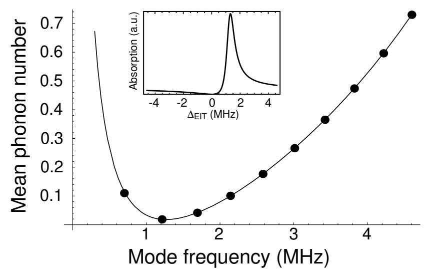

Figure 4. Mean phonon number (black dots) of the axial modes of a 10-ion string *vs* the mode frequencies, after EIT-cooling has been applied to the level scheme of Figs. 2a,2b. Here, the c.o.m. axial trap frequency is assumed to be 0.7 MHz, while $\Omega_\sigma = 20$ MHz, $\Omega_\pi = 0.5$ MHz, and $\Delta_\sigma = \Delta_\pi = 75$ MHz, giving a light shift $\delta \sim 1.3$ MHz (see inset).

this reason, EIT-cooling seems to be also suitable for optical lattices.

Acknowledgments

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