Electromagnetically-induced-transparency control of single-atom motion in an optical cavity

Tobias Kampschulte,* Wolfgang Alt, Sebastian Manz, Miguel Martinez-Dorantes, René Reimann, Seokchan Yoon, and Dieter Meschede

Institut für Angewandte Physik, Universität Bonn, Wegelerstraße 8, D-53115 Bonn, Germany

Marc Bienert and Giovanna Morigi

Theoretische Physik, Universität des Saarlandes, D-66123 Saarbrücken, Germany

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We demonstrate cooling of the motion of a single neutral atom confined by a dipole trap inside a high-finesse optical resonator. Cooling of the vibrational motion results from electromagnetically induced transparency (EIT)-like interference in an atomic A-type configuration, where one transition is strongly coupled to the cavity mode and the other is driven by an external control laser. Good qualitative agreement with the theoretical predictions is found for the explored parameter ranges. Further, we demonstrate EIT cooling of atoms in the dipole trap in free space, reaching the ground state of axial motion. By means of a direct comparison with the cooling inside the resonator, the role of the cavity becomes evident by an additional cooling resonance. These results pave the way towards a controlled interaction among atomic, photonic, and mechanical degrees of freedom.

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I. INTRODUCTION

Single emitters strongly coupled to optical resonators form a promising basis for the realization of quantum networks [1,2]. Experimental implementations include trapped ions [3], atoms [4–6], artificial superconducting qubits [7], and optomechanical devices [8]. In these platforms, the strong coupling between photons and emitters is utilized to coherently transfer quantum information between stationary qubits at the nodes and flying qubits acting as interconnects. A prerequisite for high-fidelity operations is the control of the coupling with the cavity mode, which implies spatial localization of the emitter at the subwavelength scale. This requirement is easy to fulfill for artificial atoms bound to a substrate. In ion traps the steep confinement puts relatively low requirements on cooling [9–11], while realizations based on neutral atoms in dipole traps (DTs) often require preparation of the motion close to the vibrational ground state. The latter thus calls for efficient cooling techniques, which are robust and sufficiently fast to enable viable quantum technological implementations.

Ground-state cooling of trapped atoms usually makes use of a narrow resonance, which allows one to selectively address transitions where scattering induces the loss of a quantum of vibration [12]. Such resonances can be realized by choosing a suitable dipolar transition, as in sideband cooling. In Raman sideband cooling or electromagnetically-induced-transparency (EIT) cooling, narrow transitions are obtained by coherent two-photon coupling of two stable states [13–17]. One possibility for cooling atoms inside a cavity is to perform Raman sideband cooling there, as shown in Refs. [18] and [19]. The corresponding experimental effort, however, notably increases with the number of degrees of freedom to cool. An alternative is to exploit the strong coupling at the single-photon level. In this case, the relevant narrow resonance is determined by the finite cavity lifetime [20], thus implementing a form of sideband cooling even on dipolar transitions whose radiative linewidth in free space is broader than the trap frequency [21]. In fact, the cavity plays a role similar to that of an additional resonance with linewidth 2κ [22,23]. Sub-Doppler or even sub-recoil cooling [24] can then be realized if the cavity linewidth 2κ is smaller than the trap frequency ω. For typical DTs this condition implies rather closed cavities (with a small κ), where coupling photons in and out are relatively slow and which are, thus, less suitable for fast and efficient interfaces.

In this report we experimentally characterize cooling of the vibrational motion of a trapped atom by driving a high-finesse cavity coupled to a three-level Λ transition. This work was triggered by recent experimental studies of single-photon EIT [25,26], where long trap lifetimes have been observed [26], indicating robust cooling in this system, and on recent theoretical studies [27] of cooling in this experimental setup. Here, we demonstrate cavity-assisted EIT cooling of an atom in a DT. The scheme relies on the frequency selectivity of narrow dark resonances, thus the final temperature is not limited by the resolved sideband condition (2κ ≪ ω). Moreover, we exploit the possibility of switching between EIT-like cooling and cavity cooling by simply changing the detuning of one laser to compare the cooling efficiency in the different regimes, and we show that the interplay of Raman and cavity resonances gives rise to novel and robust cooling regimes. We show that theoretical predictions and experimental results are in remarkable agreement.

II. EXPERIMENTAL SETUP

In our experiment [Fig. 1(a)] single laser-cooled neutral cesium atoms are loaded from a magneto-optical trap (MOT; 852 nm) into a far-red-detuned standing-wave DT (1030 nm) with an axial trap frequency of ω_0/2π = 0.3 MHz along the y direction and a radial trap frequency of about 1 kHz [28]. After verifying that exactly one atom has been loaded and determining its position, it is subsequently transported, using the DT as a conveyor belt, into the mode of the...
FIG. 1. (Color online) (a) Schematic of the experimental setup. A single cesium atom is trapped inside a high-finesse optical cavity and illuminated by a control laser along the dipole trap axis. A probe laser is coupled into the cavity mode and its transmission is detected by a single-photon detector. (b) Relevant bare energy levels (black) of atom and cavity, Rabi frequencies, and detunings of lasers and cavity mode. (c, d) Dressed states (gray) and scattering processes leading to cooling. Vibrational excitations are shown explicitly. Straight (curvy) arrows represent coherent (incoherent) transitions which lead to a change in energy by one vibrational quantum \( \hbar \omega \). Open arrows identify the process which mediates the mechanical action. (c) Cooling (heating) transition due to the recoil of fluorescence photons. Inset: Excitation spectrum, determining the corresponding rate, as a function of the probe frequency. This process is diffusive and can be suppressed using EIT. (d) Cooling transition due to the mechanical effect of the cavity field [horizontal (blue) arrows]. Inset: Corresponding transition rate [solid (blue) curve]. The dashed (red) curve corresponds to heating. The double Fano structure is a consequence of the strong atom-cavity coupling [27]. Diffusion and cooling or heating add up to give the rates \( A_n^0 \).
the scattering rates and can be exploited to suppress diffusion and heating processes.

The cooling dynamics is theoretically modeled approximating the dipole potential by a harmonic oscillator and using the rate-equation description in Ref. [27] in a one-dimensional treatment [31]. The model is valid for small photon numbers, \( \langle n \rangle \ll 1 \), inside the cavity and for weak mechanical coupling, characterized by a small Lamb-Dicke parameter \( \eta = |\omega_{rec}/\omega|^{1/2} \ll 1 \), where \( \omega_{rec} \) is the atomic recoil frequency and \( \omega \) is the trap frequency. The theory delivers the heating and cooling rates \( A_{\pm} \) connected with photon scattering along the blue and red sideband transitions \( |g_{2},0_k,m\rangle \rightarrow |g_{2},0_k,m \pm 1\rangle \), respectively, along the axis of motion. For cooling along the cavity axis (\( z \) axis) in the configuration in Fig. 1(a), the rates can be written in the form

\[
A^{(c)}_{\pm} = 2\gamma D + 2\gamma|T^\pm_{zc}|^2 + 2\kappa|T^\pm_{zc}|^2. \tag{1}
\]

The first term in Eq. (1), proportional to \( \gamma \) and identical for heating and cooling, describes the diffusion of the atomic motion due to mechanical effects of spontaneus decay and corresponds to the process sketched in Fig. 1(c). The second (third) term stems from processes where light is scattered by the atom (cavity), whereby the mechanical action is due to the Jaynes-Cummings coupling [Fig. 1(d)]. The exact form of the quantities \( D, T^\pm_{zc}, \) and \( T^\pm_{zc} \), and the form of \( A_{\pm} \) for cooling along other directions can be found in [27].

From the quantities \( A_{\pm} \) the cooling rate

\[
\Gamma = A_{-} - A_{+}, \tag{2}
\]

and if \( \Gamma > 0 \), the mean occupation number

\[
\langle m \rangle = \frac{A_{+}}{A_{-} - A_{+}} \tag{3}
\]

in the stationary (thermal) state at the end of cooling can be calculated [32]. The cooling rate \( \Gamma \) gives the time scale at which the stationary state of motion is reached.

The general behavior of the rates, (1), is determined by the states \( |\pm\rangle, |\rangle \rangle \): \( A_{-} \) (\( A_{+} \)) is strongly enhanced whenever the probe laser is resonant with the red (blue) sideband of one of the dressed states, i.e., for \( \delta_{PC} = \omega_{j} - \omega \) (\( \delta_{PC} = \omega_{j} + \omega \)). The linewidths \( \gamma_j \) of the dressed states determine the width of these resonances and thereby the cooling dynamics when the probe is tuned to the red sideband. In particular, for \( \gamma_j \ll \omega \), resolved sideband cooling at the corresponding dressed-state resonance can be performed.

EIT-like cooling in the cavity can be observed when the resonance condition \( \delta_{PC} = \Delta_{LA} - \Delta_{CA} \) is fulfilled. The appearance of a dark state follows from quantum interference among the three dressed states in the excitation process of the cavity-atom system and occurs when the ground state \( |g_{2},0_k\rangle \) is resonantly coupled by three photons (probe, cavity, laser) with \( |g_{1}\rangle \). In this case, the rates are

\[
A^{(c)}_{\pm} = \frac{\Omega^2_{PL} \gamma^2}{\delta^2_{PC} + \kappa^2} \eta^2 \sin^2(k_{0}z) g^2 \beta \times \frac{1 + C_{\pm}}{\nu^2(\nu^2 + \Omega^2_{PL} - \omega \pm \Delta_{LA} + \zeta C_{\pm}(\omega \pm \delta_{PC}))^2}, \tag{4}
\]

with \( C_{\pm} = C\kappa^2/(\kappa^2 + (\delta_{PC} + \omega)^2) \), whereby \( C = \beta^2/(\kappa \gamma) \) is the single-atom cooperativity. The effective coupling constant \( g = g \cos k_{0}z \) is proportional to the vacuum Rabi frequency \( g \) at an antinode of the cavity’s cosinusoidal mode function of wave number \( k \), with \( \omega_0 \) measuring the distance of the trap center from the antinode. For \( \Delta_{LA} = \Delta_{CA} \), three-photon resonance is found for \( \delta_{PC} = 0 \), and the rates, Eq. (4), take on the form of EIT cooling in free space with a modified Rabi frequency \( \Omega^2_{PL} \rightarrow \Omega^2_{PL} + 4\omega^2|\gamma' - \gamma|/\kappa \) and a modified atomic linewidth \( \gamma' = \gamma(C\kappa^2/(\kappa^2 + \omega^2) + 1) \). Hence, due the cavity-boosted Rabi frequency, lower temperatures compared to free-space EIT cooling are possible. Similarly, for large \( \delta_{PC} \) (and around \( \delta_{PL} = 0 \)), one recovers normal EIT cooling [13] in a standing wave, where the width of the EIT resonance determines the cooling.

For the parameters of the experiment, this sets the limit for the lowest achievable temperatures. To fully enter a regime where quantum interference involving the cavity determines the final vibrational occupation number given by \( C^{-1}, \kappa \ll \omega \) is required [27], a condition that is not fulfilled here. Nevertheless, signatures of such a cooling scheme can be found around the range \( |\delta_{PC}| \ll \omega \), as discussed below.

### IV. Measurements

Experimentally, the cooling efficiency is characterized by means of the survival probability \( P_s \), which is measured by first trapping a single atom inside the cavity for a certain holding time \( t \), then retrieving it from the cavity using the conveyor belt, and, finally, detecting its presence by the MOT fluorescence. After many repetitions, the measured \( P_s \) is given by the ratio between the final and the initial number of atoms. Radiative cooling and heating effects become obvious when we compare \( P_s \) with the value for atoms in the absence of near-resonant light: In the presence of the far-detuned trapping lasers only (DT and lock laser), \( P_s \) decays exponentially with a time constant of about 120 ms, limited by parametric heating [33] due to technical intensity fluctuations, mainly of the intracavity lock laser power.

We compare the survival probability with the theoretical predictions for the cooling rate \( \Gamma \equiv A^{(c)}_{2} - A^{(c)}_{1} \), determining the time scale at which the average number of vibrational excitations along the cavity axis exponentially approaches the stationary value [32]. Figure 2(a) displays a two-dimensional plot of \( \Gamma \), Eq. (2), using the rates from Eq. (1). Here, the detunings \( \delta_{PC} \) and \( \Delta_{LA} \) are varied and \( \Delta_{CA} \) is at the fixed experimental value. High cooling rates are predicted mostly when the probe laser is tuned to the red side of a dressed-state resonance (shaded areas).

Cooling and heating effects close to the dressed states \( |\pm\rangle \), \( |\rangle \rangle \) become experimentally visible when scanning the probe-cavity detuning \( \delta_{PC} \) over a wide range while \( \delta_{PL} \equiv \Delta_{LA} - \Delta_{CA} = 0 \) remains fixed (dashed-dotted line). Figure 2(b) displays the corresponding survival probabilities \( P_s \) for two holding times. The heating regions are denoted (i) and (iii). Strong losses in (ii) occur mostly at \( \delta_{PC}/2\pi \approx (2 \ldots 8) \text{ MHz} \), where the laser is tuned on the blue side of the dressed state \( |+\rangle \) and heats the motion. In (i) the detuning is \( \delta_{PC}/2\pi \approx -25 \text{ MHz} \) and the theory predicts that the motion is outside the Lamb-Dicke regime. The cooling regions are denoted (ii) [34].
Measurement of the single-atom survival probability as a function of the probe-cavity detuning \( \delta_{PC} \) for the case \( b_{LC} = 0 \) and for two holding times \( t \) inside the cavity. The parameter space corresponds to the horizontal dashed-dotted line in (a).

Figure 3(a) displays a zoom of the behavior of \( \Gamma \) in the boxed region in Fig. 2(a): A rapid change between cooling and heating regions is predicted on the scale of the trapping frequencies. Lowest temperatures are predicted along the diagonal blue stripe at the largest \( \Gamma \), corresponding to \( \delta_{PL} = 0 \), with \( m_{al} \approx 0.07 \) in the middle and down to 0.05 at the edges of the plot. Moreover, cooling is found in a second diagonal stripe, where \( \delta_{PL} \approx \omega \), and in two regions above and below the stripes, where \( \delta_{PC} \lesssim 0.2 \text{ MHz} \times 2 \pi \).

We experimentally verify this behavior by scanning the probe-cavity detuning \( \delta_{PC} \) over \( 2 \pi \times 2 \text{ MHz} \) (i.e., a few \( \omega_{DT} \)’s) around \( \delta_{PC} = 0 \) for different values of \( \delta_{LC} \). The results are displayed in Fig. 3(b): Cooling is found around \( \delta_{PL} = 0 \). It is also found when the probe laser is resonant or red-detuned from the cavity frequency \( \delta_{PC} \lesssim 0 \) and, at the same time, \( \delta_{PL} < 0 \). Heating occurs for \( 0 \lesssim \delta_{PL} \lesssim 1 \text{ MHz} \). This is also shown in Fig. 3(c), where the survival probability as a function of \( \delta_{LC} \) is displayed [26]. These observations can be understood if we consider that the lifetime of atoms exposed to the lock-laser potential is much shorter than the holding time, hence the atoms only survive if they are cooled along the cavity direction and not heated along the control laser axis. The model predicts heating along this orthogonal axis for \( \delta_{PL} > 0 \), which is maximum for (red shading) [see red shading in Fig. 3(a)]. This could explain the atom losses in this regime and why we see a single cooling peak only at \( \delta_{PL} = 0 \), corresponding to the upper diagonal stripe. This stripe corresponds to the
To quantify the performance of EIT cooling in the DT and to compare it with standard molasses cooling, we apply microwave sideband spectroscopy by making the lattice slightly state dependent [35]. Figure 4 shows spectra taken with EIT- and molasses-cooled atoms, respectively. The significant reduction in the $m \rightarrow m - 1$ and $m \rightarrow m - 2$ sideband transitions compared to the $m \rightarrow m + 1$ transition indicates already a high population in the ground state of axial motion (along $y$) for the EIT-cooled atoms. In performing robust adiabatic passages on the $m \rightarrow m - 1$ transition, we infer, for the EIT-cooled (molasses-cooled) atoms, a steady-state temperature of $7.0 \pm 0.5 \mu K$ $(31 \pm 6 \mu K)$, corresponding to a final ground-state occupation of $0.78 \pm 0.02$ $(0.29 \pm 0.05)$, respectively. From the variation in the duration of the EIT cooling, a cooling rate of about $1 kHz$ has been inferred, compatible with predictions in Ref. [15].

V. DISCUSSION

With our setup we have successfully demonstrated EIT cooling applied to neutral atoms in a DT. When comparing the measurement of the survival probability with the corresponding one in the presence of the resonator, there is an obvious difference on the red side ($\delta_{PC} < 0$) of the EIT condition. This is because the cavity adds a new resonance, extending the cooling region to a larger range of probe-cavity detunings $\delta_{PC}$, thereby making the cooling more robust. For this reason, these dynamics are also suitable for simultaneously cooling several degrees of freedom, for instance, atomic arrays [17,36]. Moreover, as shown in Fig. 3(b), in CEIT different cooling profiles can be achieved by changing $\delta_{LC}$, reflecting the additional interference effect and resonance, which are absent in free space.

In conclusion, this work has investigated a scheme of CEIT cooling and provides a comparison between the efficiency of free-space cooling and that of cavity cooling. These techniques can be extended for cooling optomechanical systems [37] coupled to a single emitter [38]. Our setup, moreover, can serve as a transducer among the vibrational, electronic, and photonic degrees of freedom, thereby realizing a continuous-variable quantum interface with single atoms [39].

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