Fast ground state laser cooling of trapped atoms using electromagnetically induced transparency (EIT)

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We present a laser cooling method for trapped atoms which achieves ground state cooling by exploiting quantum interference in a driven Λ-shaped arrangement of atomic levels. By appropriately designing the absorption profile with a strong coupling laser, the cooling transitions induced by a cooling laser are enhanced while heating by resonant absorption is suppressed through quantum interference (EIT).

An intuitive explanation of the technique is given in terms of dressed states of the atom. We study the cooling process with a Monte-Carlo simulation of the full quantum mechanical model for one motional degree of freedom and compare the results to a rate equation description. The rate equation has been derived rigorously from the master equation and agrees with the intuitive picture.

The method requires only two continuous lasers and is not based on the strong confinement condition, i.e. it does not impose restrictions on the transition linewidth. Therefore it is significantly more efficient, yet technically simpler than existing methods of sideband cooling. It is also insensitive to laser frequency fluctuations and it works equally well with four levels, e.g. with the $S_{1/2}$ to $P_{1/2}$ Zeeman sublevels of a Ba^+ or Ca^+ ion. Simultaneous cooling of several vibrational modes with similar frequencies as well as a smooth transition from Doppler to ground state cooling are possible with this method.

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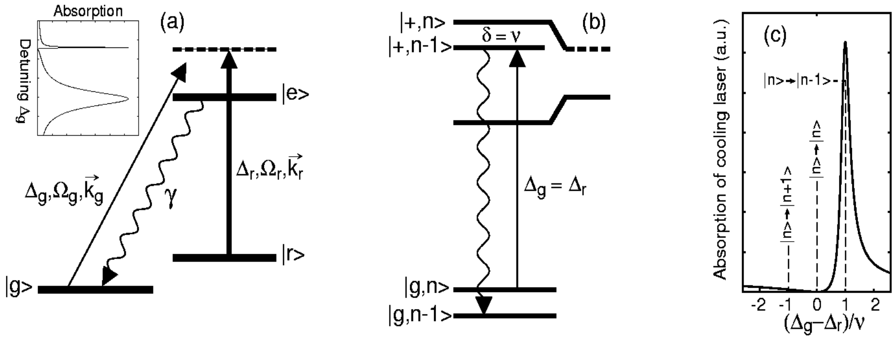

Figure 1: (a) Levels and transitions of the cooling scheme. Such an arrangement is found in many species used for ion trapping. The cooling (coupling) laser is denoted by index g (r). The inset shows schematically the absorption rate on $|g\rangle \rightarrow |e\rangle$ when the atom is strongly excited above resonance on $|r\rangle \rightarrow |e\rangle$. (b) Dressed levels created by coupling laser including motional states $|n\rangle$. For EIT cooling the AC Stark shift δ is equal to the trap frequency ν. (c) Absorption of cooling laser around $\Delta_g = \Delta_r$ showing the probabilities of carrier ($|n\rangle \rightarrow |n\rangle$) and sideband ($|n\rangle \rightarrow |n \pm 1\rangle$) transitions.

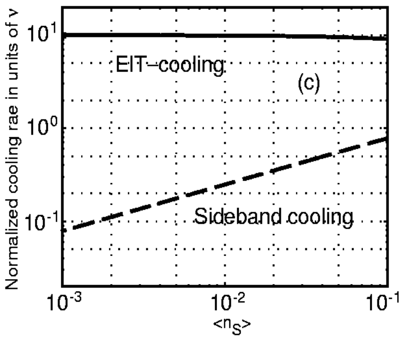

Figure 2: Normalized cooling rate, in units of the vibrational frequency ν, *vs.* steady state value of vibrational excitation $\langle n_S \rangle$, for conventional sideband cooling with detuning $-\nu$, and for EIT–cooling with $\gamma = 10\nu$ and optimum parameters $\delta = \nu$ (δ is the AC Stark shift) and $\Delta = \gamma/\sqrt{16\langle n_S \rangle}$.