Double-EIT ground-state laser cooling without blue-sideband heating

J. Evers and C. H. Keitel

1 Theoretische Quantendynamik, Fakultät für Physik und Mathematik
Universität Freiburg - Hermann-Herder-Straße 3, 79104 Freiburg, Germany
2 Max-Planck-Institut für Kernphysik - Saupfercheckweg 1, 69117 Heidelberg, Germany

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Abstract. – We discuss a laser cooling scheme for trapped atoms or ions which is based on
double electromagnetically induced transparency (EIT) and makes use of a four-level atom in
tripod configuration. The additional fourth atomic state is coupled by a strong-coupling laser
field to the upper state of the usual three-level setup of single-EIT cooling. This effectively
allows to create two EIT structures in the absorption spectrum of the system to be cooled, which
may be controlled by the coupling laser field parameters to cancel both the carrier- and the blue-
sideband excitations. In leading order of the Lamb-Dicke expansion, this suppresses all heating
processes. As a consequence, the double-EIT scheme can be used to lower the cooling limit by
a factor of order of the Lamb-Dicke parameter squared as compared to single-EIT cooling.

Introduction. – Many current experiments involving the preparation or manipulation of
atoms and ions require a precise coherent control of the system of interest. This does not only
apply to internal degrees of freedom, but also to the external motional degrees of freedom.
In the last few years, the laser cooling of trapped ions or atoms has therefore been a subject
of intense research and is now a routine tool in many laboratories. Starting from the first
observation of laser cooling [1], many interesting applications have been made possible by
laser cooling. Examples are the direct observation of quantum jumps [2], the preparation of
atoms in the motional ground state [3], and high-precision spectroscopy [4].

Apart from cooling on dipole-forbidden transitions [3,5] and cooling by stimulated Raman
transitions [6], cooling facilitated by electromagnetically induced transparency (EIT) [7,8] is
a promising recent technique to reach the mechanical ground state of trapped atoms or ions.
EIT cooling has already been observed experimentally [9]. Once a trapped atom reaches the
Lamb-Dicke regime, e.g., by unresolved Doppler cooling, the interaction with a cooling laser
field may excite the atom by three kinds of processes. Carrier excitations involve an excitation
of the internal electronic degree of freedom of the atom without a change of the motional
quantum number. Processes where simultaneously with the internal excitation the motional
quantum number is increased (decreased) are known as blue (red) sideband excitations. Both

(*) E-mail: evers@physik.uni-freiburg.de
(**) E-mail: keitel@mpi-hd.mpg.de
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excitation–de-excitation cycles involving carrier- and blue-sideband excitations may lead to a heating of the trapped system, while red-sideband excitations may cool the system. The basic idea of EIT cooling is to design the absorption properties of the sample to be cooled such that carrier excitations are inhibited, and such that red-sideband transitions dominate over blue-sideband transitions. The finite cooling limit is then reached if the heating and the cooling rates become equal. The incoherent thermal motion, however, is a source of decoherence and disturbs the precise coherent control of the system. One way to resolve this problem is to find control schemes for “hot” systems which do not require a cooling to the ground state [10]. Nevertheless, many recent theoretical proposals rely on an atomic or ionic system cooled to the motional ground state in order to allow for a precise control and to avoid decoherence. Typical examples for this are quantum communication or information schemes.

Therefore in this article we propose a “double-EIT” cooling scheme which in addition to the three-level Λ-setup in the usual EIT scheme makes use of an additional third ground state. This state is coupled by a strong-coupling laser to the upper state, see fig. 1. This effectively allows to create two independent EIT-structures in the absorption spectrum of the trapped atom, which can be controlled by the two coupling laser fields to cancel the carrier- and the blue-sideband transitions, respectively. With this technique, the dominant heating processes of single-EIT cooling are suppressed in double-EIT cooling. Thus the predicted cooling limit of the double-EIT scheme is suppressed by a factor of order $\eta^2$ as compared to conventional EIT cooling, where $\eta$ is the Lamb-Dicke parameter. For many cooling setups, already single-EIT cooling requires additional repump fields because the upper state decays to more than two lower states. Instead of repumping the system arbitrarily, a suitable choice for the parameters and a frequency and intensity stabilization of the pump laser field then leads to double-EIT cooling and thus to improved cooling performance. Therefore with the double-EIT scheme the unwanted additional decay pathways can become an advantage.

The double-EIT scheme. — The system consists of a trapped atom confined in a harmonic potential with trap frequency $\nu$ and mass $M$. Internally, the atom has one upper state $|e\rangle$ and three lower states $|i\rangle$ ($i \in \{1, 2, 3\}$) which are connected by dipole-allowed transitions to the upper state (see fig. 1). Each of the transitions is driven by a laser field with Rabi frequency $\Omega_i$ and detuning $\Delta_i = \omega_{Li} - (\omega_{ei} - \omega_i)$ ($i \in \{1, 2, 3\}$) where $\omega_{Li}$ is the frequency of the $i$-th laser field and $\hbar \omega_j$ ($j \in \{e, 1, 2, 3\}$) is the energy of the atomic state $|j\rangle$. The upper state may further decay to the lower states with the decay rates $\gamma_i$, respectively. Thus the system Hamiltonian for the coherent evolution is given by [11, 12]

$$H = \hbar \nu a^\dagger a + \hbar \sum_{j=1}^{3} \Delta_j |j\rangle \langle j| + \hbar \sum_{j=1}^{3} \frac{\Omega_j}{2} \left( e^{-ik_j \cos(\phi_j) x} |e\rangle \langle j| + \text{H.c.} \right),$$

(1)
are chosen to satisfy eqs. (6), (7). The trap frequency is maximized. Here, the parameters are $\Omega_{\text{transition}}$ and the blue-sideband heating are completely cancelled, while the red-sideband cooling is of these zeros and of the maximum of the absorption. For appropriately chosen parameters, the carrier transition and the coupling fields only. This allows for simple approximate analytical results [8]. The three decay channels are considered in full in the numerical analysis. The internal state dynamics of the atoms is then given by the following equations of motion for the density matrix $\rho$ [13]:

$$\dot{\rho}_{jj} = i \frac{\Omega_j}{2} (\rho_{je} - \rho_{ej}) + \delta_{j3}\gamma \rho_{ee},$$

$$\dot{\rho}_{je} = -\left(i\Delta_j + \delta_{j3} \frac{\gamma}{2}\right) \rho_{je} - i \frac{\Omega_j}{2} \rho_{ee} + i \sum_{l=1}^{3} \frac{\Omega_l}{2} \rho_{lj},$$

$$\dot{\rho}_{jk} = i(\Delta_k - \Delta_j) \rho_{jk} - i \frac{\Omega_j}{2} \rho_{ek} + i \frac{\Omega_k}{2} \rho_{je},$$

for $j, k \in \{1, 2, 3\}$ with $j \neq k$. $\delta_{jk}$ is the Kronecker delta, and the equations for the other density matrix elements are obtained using the relations $\text{Tr}(\rho) = 1$ and $\rho_{jk} = \rho_{kj}^*$. In the following, the two transitions $1 \leftrightarrow e$ and $2 \leftrightarrow e$ are assumed to be driven by coupling laser fields which effectively dress the atom in order to modify the interaction with the third laser field on the cooling transition $3 \leftrightarrow e$. The cooling effect depends on the scattering rate of the cooling laser field. A typical scattering spectrum of the cooling laser is shown in fig. 2(a). The spectrum may be understood as consisting of two Fano-like structures characteristic for EIT.

where $k_j \ (j \in \{1, 2, 3\})$ are the wave vectors of the coupling laser field traveling in directions given by the angles $\phi_j$, $x$ is the position operator, and $a(a^\dagger)$ is the annihilation (creation) operator for a motional quantum. The master equation for the system density operator $\rho$ reads $\frac{d\rho}{dt} = -\frac{1}{\hbar} [H, \rho] + \mathcal{L}_{\text{SE}} \rho$. Here, the super-operator $\mathcal{L}_{\text{SE}}$ describing the spontaneous decays with angular distribution $\mathcal{N}_j(\theta)$ $(j = 1, 2, 3)$ acts as $[[\cdot, \cdot]]_+ \text{ denotes the anti-commutator}$ [11]

$$\mathcal{L}_{\text{SE}} \rho = -\sum_{j=1}^{3} \frac{\gamma_j}{2} \left( [\langle e \rangle, \rho]_+ - 2 \int_{-1}^{1} \mathcal{N}_j(\theta) \langle j \rangle \langle e \rangle e^{ik_j x \cos \theta} \rho e^{-ik_j x \cos \theta} \langle j \rangle d\cos \theta \right). \tag{2}$$

In the first step of the analytical calculation, we neglect the external degrees of freedom [7]. Furthermore, we only consider spontaneous decay on the cooling transition $3 \leftrightarrow e$ with a rate equal to the total upper state decay rate $\gamma$, thus assuming the other transitions to interact with the coupling fields only. This allows for simple approximate analytical results [8]. The three decay channels are considered in full in the numerical analysis. The internal state dynamics of the atoms is then given by the following equations of motion for the density matrix $\rho$ [13]:

$$\dot{\rho}_{jj} = i \frac{\Omega_j}{2} (\rho_{je} - \rho_{ej}) + \delta_{j3}\gamma \rho_{ee},$$

$$\dot{\rho}_{je} = -\left(i\Delta_j + \delta_{j3} \frac{\gamma}{2}\right) \rho_{je} - i \frac{\Omega_j}{2} \rho_{ee} + i \sum_{l=1}^{3} \frac{\Omega_l}{2} \rho_{lj},$$

$$\dot{\rho}_{jk} = i(\Delta_k - \Delta_j) \rho_{jk} - i \frac{\Omega_j}{2} \rho_{ek} + i \frac{\Omega_k}{2} \rho_{je},$$

for $j, k \in \{1, 2, 3\}$ with $j \neq k$. $\delta_{jk}$ is the Kronecker delta, and the equations for the other density matrix elements are obtained using the relations $\text{Tr}(\rho) = 1$ and $\rho_{jk} = \rho_{kj}^*$. In the following, the two transitions $1 \leftrightarrow e$ and $2 \leftrightarrow e$ are assumed to be driven by coupling laser fields which effectively dress the atom in order to modify the interaction with the third laser field on the cooling transition $3 \leftrightarrow e$. The cooling effect depends on the scattering rate of the cooling laser field. A typical scattering spectrum of the cooling laser is shown in fig. 2(a). The spectrum may be understood as consisting of two Fano-like structures characteristic for EIT.

![Absorption spectrum](image-url)

Fig. 2 – Cooling laser absorption rate. (a) Double-EIT. As there are two EIT structures, the absorption vanishes at two values for the detunings $\Delta_3$ of the cooling laser. The vertical lines mark the positions of these zeros and of the maximum of the absorption. For appropriately chosen parameters, the carrier transition and the blue-sideband heating are completely cancelled, while the red-sideband cooling is maximized. Here, the parameters are $\Omega_1 = \Omega_2 = \gamma$, $\Omega_3 = \gamma/2$, $\Delta_1 = \gamma$. The other parameters are chosen to satisfy eqs. (6), (7). The trap frequency is $\nu \approx 0.3\gamma$. (b) Absorption spectrum for simultaneous cooling at two different trap frequencies ($\nu_2 = 1.5 \nu_1$) with triple-EIT.
which may be controlled independently by the two strong-coupling laser fields. For a three-
level Λ-type atom, the corresponding scattering spectrum only contains one such structure.

Taking into account the harmonic motion of the atom with frequency ν, the carrier excita-
tion (∣3, n⟩ → ∣e, n⟩) occurs at ∆3 = ∆1. In the following, we assume these detunings to be
positive. The blue-sideband excitation due to the process ∣3, n⟩ → ∣e, n + 1⟩ is at detuning
∆3 = ∆1 − ν, as the remaining energy is required to create a quantum of the harmonic motion.
The red-sideband excitation (∣3, n⟩ → ∣e, n − 1⟩) is at ∆3 = ∆1 + ν (see fig. 2). Thus it is
clear that in order to achieve efficient cooling of the system, the scattering spectrum has to
be modified such that it has minima at ∆3 − ∆1 = 0, −ν and a maximum at ∆3 − ∆1 = ν. In
order to obtain conditions for the laser field parameters, we evaluate the scattering spectrum.
We keep the cooling field to all orders, as in general the cooling field is not assumed to be
weak as compared to the coupling fields. In the resulting expression, we set ∆3 = ∆1 + ν and
∆2 = ∆1 − ν and maximize with respect to ν. One of the solutions is the condition for ν, as
the laser parameters need to be chosen such that the scattering rate has its maximum value
at ∆3 = ∆1 + ν. This yields the following conditions for the laser parameters:

\[ \Delta_3 = \Delta_1, \quad \Delta_2 = \Delta_1 - \nu, \quad \nu = \frac{1}{2} \left( \sqrt{\Delta_1^2 + \Omega_1^2 + \Omega_2^2/2 + \Omega_3^2} - \Delta_1 \right). \]  

(6)  

(7)

In fact, these conditions have been used in fig. 2(a). For Ω2 = 0, the conditions eqs. (6), (7)
for the detuning and for ν reduce to the corresponding result for the three-level case [8].
The interpretation of these results may be given in terms of the dressed state of the four-level
atomic system driven by the two strong-coupling laser fields with Rabi frequencies Ω1, Ω2. The
maxima in the scattering spectrum shown in fig. 2 correspond to the position of these dressed
states, and the widths of the peaks in the spectrum correspond to the dressed decay rates.
The position of one of the narrow dressed states has to be adjusted by the laser parameters such
that it is at ∆3 + ν and coincides with the red-sideband transition frequency. The minima in
the scattering spectrum arise from two-photon resonance conditions of the cooling laser field
with each of the two coupling laser fields at ∆3 = ∆1 and ∆3 = ∆2 = ∆1 − ν.

At second-order perturbation theory in the Lamb-Dicke parameter, the system evolution
may be described by a rate equation for the population Π(n) of the motional number states
∣n⟩ which is given by [7,11,12]

\[ \frac{d}{dt} \Pi(n) = A_- [(n + 1)\Pi(n + 1) - n\Pi(n)] + A_+ [n\Pi(n - 1) - (n + 1)\Pi(n)]. \]  

(8)

From this, one may obtain an equation for the time dependence of the mean number of vibration excitations ⟨n⟩ = \( \sum_{k=0}^{\infty} k^3 \Pi(k)k \) which is given by ⟨\dot{n}⟩ = −(A_− − A_+)⟨n⟩ + A_+, with
the cooling rate \( W = A_- - A_+ \) and the steady-state value ⟨n⟩ss = A_+ / W. The coefficients
A_± can be obtained by expanding the Hamiltonian describing the coherent interaction of the
atom with the laser fields with respect to the Lamb-Dicke parameter. The first-order term of
this expansion is \( V_1 = \frac{i}{2} \sum_{j=1}^{3} k_j \cos(\phi_j)\Omega_j (\langle j | - | e \rangle \langle e | j \rangle) \). The fluctuation spectrum of this operator is given by

\[ S(\omega) = \frac{1}{2M^2 \nu^2} \int_0^\infty e^{i\omega \tau} \langle V_1(\tau)V_1(0) \rangle_{ss} d\tau, \]  

(9)

where the subindex “ss” denotes the steady state of the expectation value. The coefficients
A_± are then \( A_\pm = 2 \Re \{ S(\pm \nu) \}. \) As in the single-EIT scheme with three-level Λ-type atoms,
we set \( \Delta := \Delta_1 = \Delta_3 \) in order to fulfill eq. (6) and thus to eliminate the carrier excitations.
Fig. 3 - Numerical simulations of the cooling dynamics. (a) Cooling of a Ca\(^{+}\)-ion. The parameters are \(\nu = 0.1 \gamma\), \(\Delta_1 = \Delta_3 = 2.5 \gamma\), \(\Delta_2 = 2.4 \gamma\) and \(\eta = 0.145\). (i) Single-EIT cooling with \(\Omega_1 = \gamma\) and \(\Omega_3 = 0.1 \gamma\). (ii) Double-EIT cooling with \(\Omega_1 = 0.8 \gamma\), \(\Omega_2 = 0.8944 \gamma\) and \(\Omega_3 = 0.1 \gamma\). (iii) Double-EIT cooling with \(\Omega_1 = \Omega_2 = \Omega_3 = 0.645 \gamma\). The dashed horizontal line marks the single-EIT cooling limit, and the diagonal line shows an exponential decay with the single-EIT cooling rate for parameters as in (i). (b) EIT-cooling of Hg\(^{+}\)-ions. The parameters are \(\gamma = 69\,\text{MHz}\), \(\gamma_1 = \gamma_2 = \gamma_3 = \gamma/3\), \(\nu = 1.5\,\text{MHz}\), \(\Omega_3 = 4\,\text{MHz}\), \(\Delta_1 = \Delta_3 = 80\,\text{MHz}\), \(\eta_1 \cos(\phi_1) = \eta_2 \cos(\phi_2) = 0.13\), \(\eta_3 \cos(\phi_3) = -0.13\). (i) Single-EIT cooling with repump field: \(\Delta_2 = 0\), \(\Omega_1 = 21\,\text{MHz}\), \(\Omega_2 = 8\,\text{MHz}\). (ii) Double-EIT cooling as in (i), but with \(\Delta_2 = \Delta_1 - \nu\). (iii) Double-EIT cooling with \(\Delta_2 = \Delta_1 - \nu\), \(\Omega_1 = 4\,\text{MHz}\), \(\Omega_2 \approx 30\,\text{MHz}\) according to eq. (7).

This yields

\[
\frac{A_{\pm}}{\eta^2} = \frac{\Omega_1^2}{\Omega_1^2 + \Omega_3^2} \frac{\gamma\nu^2\Omega_3^2}{4 \{((\Omega_1^2 + \Omega_2^2)/4 - \nu(\nu \mp \Delta)) + \mathcal{E}_{\pm}\}^2 + \gamma^2\nu^2},
\]

with

\[
\mathcal{E}_{\pm} = \mp \frac{\nu\Omega_2^2}{4(\Delta - \Delta_2 + \nu)}.
\]

\(\eta = \eta_1 \cos(\phi_1) - \eta_3 \cos(\phi_3)\) is the relevant Lamb-Dicke parameter, where \(\eta_i = \kappa_i \sqrt{\hbar/2M\nu}\) \((i = 1, 2, 3)\) are the Lamb-Dicke parameters of laser field mode \(i\). This expression is the same as the corresponding result for the single-EIT three-level case \([8]\) except for the additional contribution \(\mathcal{E}_{\pm}\) in the denominator, which depends on the parameters \(\Omega_2\), \(\Delta_2\) of the second coupling laser field. For \(\Omega_2 = 0\), one has \(\mathcal{E}_{\pm} = 0\) and thus obtains the result for the three-level case. On applying the other conditions on the laser field parameters, eqs. (6), (7), for the optimum cooling conditions, the rates \(A_{\pm}\) become

\[
A_+ = 0, \quad A_- = \eta^2 \frac{\Omega_1^2}{\Omega_1^2 + \Omega_3^2} \frac{\Omega_3^2}{\gamma},
\]

such that the cooling rate and the cooling limit simplify to

\[
W^c = \eta^2 \frac{\Omega_1^2}{\Omega_1^2 + \Omega_3^2} \frac{\Omega_3^2}{\gamma}, \quad \langle n \rangle^c_{ss} = 0.
\]

Here, the index “c” denotes the values obtained after applying the conditions eqs. (6), (7). Thus in this order of the expansion in the Lamb-Dicke parameter, the predicted cooling limit is zero. We expect next-higher-order corrections \(A_+ \sim \mathcal{O}(\eta^4)\), and thus \(\langle n \rangle^c_{ss} \sim \mathcal{O}(\eta^2)\). Also, the double-EIT configuration increases the cooling rate as compared to single-EIT, as the two values for \(A^c_-\) are the same in both setups, while one has \(A^c_+ > 0\) for single-EIT cooling.
In fig. 3(a), we show results of a numerical simulation of the cooling dynamics for atomic parameters of a Ca$^+$-ion [14]. $\langle n \rangle$ is the expectation value of the vibrational quantum number shown on a logarithmic scale against time $t$. Curve (i) shows the single-EIT setup, which is in good agreement to both the cooling limit (dashed horizontal line) and the cooling rate (solid diagonal line) obtained by the single-EIT rate equation results. Curve (ii) shows double-EIT cooling for the same trap frequency, detuning, Lamb-Dicke parameter and cooling laser field intensity as in (i). In this configuration, the cooling limit is suppressed by about a factor of the Lamb-Dicke parameter $\eta$ squared, while the cooling rate is comparable to the single-EIT case. In the final stage of EIT cooling close to the motional ground state, the upper-state population and thus the spontaneous-emission rate is so low that an average over many wave functions is required to obtain a reliable prediction for the cooling limit from a quantum Monte Carlo simulation. This especially holds for double-EIT cooling, where the upper-state excitation is even lower than in single-EIT cooling. Thus we evaluated the cooling dynamics by a numerical integration of the full master equation including the first ten harmonic-oscillator states to avoid losses at the border of the simulated level system. The results obtained by the numerical integration are consistent with results estimated from full quantum Monte Carlo simulations. The last curve (iii) shows double-EIT cooling with the same parameters as in (ii) except for the Rabi frequencies, which are all set to $\Omega_i = 0.645 \gamma$ ($i = 1, 2, 3$). Thus here the cooling laser field is not weak as compared to the driving laser fields. Whereas the cooling limit is similar to the single-EIT cooling case as in (i), the cooling rate is more than one order of magnitude larger, thus allowing for a faster preparation of the final state. Figure 3(b) shows the corresponding results for $^{199}$Hg$^+$-ions, e.g. with upper state $P_{1/2}$ ($F' = 1, m_F = 1$) and three lower states $S_{1/2}$ ($F = 1, m_F = 1, 0$) and $S_{1/2}$ ($F = 0, m_F = 0$) [15]. With single-EIT cooling, the population decaying to the third lower state has to be repumped to the single-EIT subspace, which induces additional heating. The cooling dynamics for a typical setup is shown in curve (i). By modifying the detuning of the repump field such that the double-EIT conditions eqs. (6), (7) are fulfilled, the cooling limit can be lowered considerably, as shown in (ii). Note, however, that the EIT-scheme requires frequency- and intensity-stabilized laser fields which normally is not needed for repumping. Curve (iii) shows double-EIT cooling with parameters as in (ii), except for modified Rabi frequencies of the two driving fields $\Omega_1, \Omega_2$, which results in a further significant lowering of the cooling limit. (Single-EIT with Rabi frequencies as in (iii), but $\Delta_2 = 0$, yields heating of the system.) Note that for the Hg$^+$-ion the decay rates to all of the lower states and the additional heating due to the pump field have been taken into account. Also, we verified that the improved cooling dynamics is a double-EIT effect by slightly changing the detuning $\Delta_2$ from the optimum value $\Delta_1 - \nu$, yielding higher cooling limits for both lower and higher detunings.

Discussion and summary. – The double-EIT scheme differs from the conventional single-EIT scheme in that the absorption spectrum is designed such that both the carrier- and the blue-sideband excitations are inhibited. This suppresses the heating processes and the cooling limit by a factor of the order $\eta^2$. As with the conventional single-EIT mechanism, simultaneous cooling in three dimensions is possible if the trap frequencies along the three axes are not too different such that the red-sideband absorption frequencies of all directions are within the narrow peak in the scattering spectrum at $\Delta_3 - \Delta_1 = \nu$. However, while the double-EIT scheme generally improves the cooling properties as compared to the single-EIT case, a simultaneous cooling along more than one motional axis to the ground state with efficiency as in the one-dimensional case requires the trap frequencies to be equal, as otherwise the heating processes cannot be cancelled exactly for all directions at the same time. By coherently coupling more than three lower levels to the upper state, the cooling scheme
can also be extended to multiple-EIT cooling. Then simultaneous EIT-cooling at different trap frequencies without blue-sideband heating is possible. Figure 2(b) shows triple-EIT with four lower levels, where \( n_1 \) (\( n_2 \)) is the motional quantum number for trap frequency \( \nu_1 \) (\( \nu_2 \)). Alternatively, multiple-EIT can be used to cancel further heating processes. At higher order in \( \eta \), however, also the heating via scattering of the cooling fields needs to be taken into account.

It should be noted that in some systems already single-EIT cooling requires additional repump fields because the upper state decays to more than two lower states. Instead of repumping the system arbitrarily, a suitable choice for the parameters and a frequency and intensity stabilization of the pump laser field then leads to double-EIT cooling and thus to improved cooling performance. Therefore, here the disadvantage of additional decay channels becomes an advantage. Other possible systems for double-EIT cooling are, e.g., Ne [16], Rb, Yb, or Cs. Depending on the choice of the upper state, the latter systems also allow for multiple-EIT cooling with more than three lower states.

In summary, we have presented a laser cooling scheme which allows to efficiently reach the motional ground state of a trapped atom or ion. With the help of two coupling laser fields, the scattering spectrum for the cooling laser field is designed such that both carrier- and blue-sideband excitations are inhibited, thus eliminating all heating processes in leading order of an expansion in the Lamb-Dicke parameter \( \eta \). As compared to the conventional single-EIT scheme, this double-EIT scheme allows to lower the cooling limit by a factor of order \( \eta^2 \).

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