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Continuous polarization-gradient precooling-assisted velocity-selective coherent population trapping

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We show that polarization-gradient cooling occurs in the Λ system, simultaneously with velocity-selective coherent population trapping (VSCPT). Starting with a Doppler temperature sample, this process precools atoms and contains them, to within twice the recoil velocity, a range efficiently capturable by VSCPT. For sodium, this cooling may enhance the rate of three-dimensional VSCPT by 200 times over the rate achievable from Doppler precooling alone. We estimate that in 8 msec, for example, the atoms would be cooled in three dimensions to one-fourth the recoil temperature.

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Recently, there has been a great deal of interest in multilevel atoms that undergo velocity-selective coherent population trapping (VSCPT) into a zero-velocity dark state. Aspect *et al.* [1] used a folded three-level (Λ) system excited by a pair of traveling waves to reach subrecoil temperatures in one dimension. Ol'shanii and Minogin [2] have shown theoretically that a $J=1\leftrightarrow J'=1$ transition can be used to create a three-dimensional dark state when excited by three pairs of traveling waves. However, since VSCPT occurs via a random walk in momentum space [1], in three dimensions the efficiency would fall off rapidly as a function of velocity, with a capture range of the order of the recoil velocity. Therefore, in order to significantly populate the three-dimensional (3D) dark state, it is necessary to precool atoms close to the recoil limit. It is advantageous for this precooling to coexist with VSCPT; otherwise, the random walk causes most of the atoms to heat up to velocities beyond the capture range. This type of precooling and velocity confinement does not exist in the various VSCPT schemes considered so far [1–5].

In this paper, we present a mechanism under which polarization-gradient cooling efficiently slows atoms from a sample at the Doppler limit to nearly the recoil limit. Unlike other methods [6] of sub-Doppler cooling, this cooling occurs under the same conditions as those required for VSCPT. We illustrate the basic mechanism in one dimension using a Sisyphus model [7]. The predictions of this model are consistent with numerical results obtained from continued fractions. In addition, we use Monte Carlo simulations to determine the enhancement of VSCPT in one dimension. Finally, we also discuss the generalization of this scheme to three dimensions. This mechanism opens up the possibility of continuously cooling a large number of atoms to subrecoil temperatures. This scheme differs significantly from Ref. [1] in that it uses standing waves, it requires laser detuning, and the resulting cooling provides "walls" in momentum space which confine the atoms and greatly enhance the pumping rate into the dark state.

The basic features of this cooling technique are well demonstrated in one dimension by a Λ system excited by a pair of Raman resonant standing-wave fields. An excellent sample [1] of such a system is a $J=1\leftrightarrow J'=1$ transition excited by a pair of opposite circularly polarized standing waves. Efficient cooling is obtained in the case where the average detuning δ is positive and the phase difference χ between the standing waves is $\pi/4$.

The electric field can be expressed as

$$\mathbf{E}=\{-\hat{\sigma}_{-}E_{10}\sin(k_1 z)[\exp(-i\omega_1 t)+\text{c.c.}] +\hat{\sigma}_{+}E_{20}\sin(k_2 z+\chi)[\exp(-i\omega_2 t)+\text{c.c.}]\}/2\ , \qquad (1)$$

where z is the c.m. position of the atom. We express the Rabi frequencies as $g_1\equiv g_{10}\sin(k_1 z)$ and $g_2\equiv g_{20}\sin(k_2 z+\chi)$. We consider only the case of equal detunings on each leg of the Λ system (necessary condition for VSCPT) and $g_{10}=g_{20}\equiv g_0$.

In order to find the force on a moving atom in this system, we will use the diagonalized basis states: $|-\rangle\equiv\cos\theta|a\rangle-\sin\theta|b$, $|W\rangle\equiv\cos\beta|+\rangle-\sin\beta|e\rangle$, and $|S\rangle\equiv\sin\beta|+\rangle+\cos\beta|e\rangle$. Here, $\theta\equiv\tan^{-1}(g_1/g_2)$ and $2\beta\equiv\tan^{-1}(g/\delta)$, with $|+\rangle\equiv\sin\theta|a\rangle+\cos\theta|b\rangle$. The force is given by $f=f_p+f_c$, where

$$\begin{aligned} f_p&=-\nabla\varepsilon_W(\Pi_{WW}-\Pi_{SS})\ ,\\ f_c&=-\varepsilon_W\nabla\theta 2\,\mathrm{Re}\Pi_{-W}+g\nabla\theta\,\mathrm{Re}\Pi_{-s}+\nabla g\,\mathrm{Re}\Pi_{WS}\ . \end{aligned} \qquad (2)$$

Here $\hat{\Pi}$ is the density operator $g\equiv\sqrt{g_1^2+g_2^2}$ and ε_W is the energy of $|W\rangle$. Physically, f_p is the force associated with the populations of the dressed states, and f_c is the force associated with the coherences between the dressed states.

We consider the case where $\beta^2\cong g^2/4\delta^2\ll 1$. In this limit, $|S\rangle\cong e\rangle$, $|W\rangle\cong|+\rangle$, and the equations of motion simplify considerably. We are interested in low velocities

($v \ll \Gamma/k$), so that we can eliminate the state $|e\rangle$ adiabatically [8]. In addition, it can be shown [9] that $f_c \ll f_p$ for nonzero values of f_c and f_p, so that the force simplifies to $f \cong f_p = -\nabla \varepsilon_W \Pi_{WW}$.

Note that $\varepsilon_W \cong g^2/4\delta$ is proportional to the sum of the intensities of the two standing waves. For $\chi = \pi/2$, this is a constant, so that $f=0$. In addition, the force vanishes at $\chi=0$. To see why, note that, for this phase, $g_1 = g_2$ everywhere, so that there is no motional mixing. As a result, all the atoms end up in $|-\rangle$, independent of velocity, and the force vanishes.

We now estimate the force and the cooling coefficients for the case of $\chi = \pi/4$. Figure 1(a) illustrates the Rabi frequencies for this phase. Consider an atom starting from the node P in the state $|-\rangle = |b\rangle$. It will, on average, stay in state $|b\rangle$ for a time τ_p, which is given by the inverse of the optical pumping rate $\alpha_p \cong \Gamma g^2/8\delta^2$, and then decay by spontaneous emission to the local $|-\rangle$ state. Consider a velocity such that the atom travels to the next node Q in this time. Thus, once the atom reaches node Q, it will decay to state $|-\rangle = |a\rangle$. We now estimate the force it experiences during this flight.

Since $\Pi_{WW} \cong \Pi_{++}$, the population of the $|W\rangle$ state simply goes from 0 to 1 as the atom goes from P to Q. Π_{WW} is illustrated in Fig. 1(b). As can be seen, few atoms are in the $|W\rangle$ state during the first half of the flight, while almost all the atoms are in the $|W\rangle$ state during the second half. Figure 1(c) shows the corresponding plot of the energy of the $|W\rangle$ state. The circles on the energy curve indicate that most of the atoms are in the corresponding state. As can be seen, very few atoms fall down the hill during the first half, while many atoms climb the hill during the second half. As a result, there is net cooling during this optical pumping cycle.

To see what happens during the flight from the node Q to the node P', note that the distance is three times as large, and the average optical pumping rate α_p (which is proportional to ε_W), is about twice as large. Therefore, there would be about six optical pumping cycles while going from Q to P'. After each cycle, the atom starts from the local $|-\rangle$ state and rotates into the $|W\rangle$ state. However, due to the short duration of the optical pumping cycle, a very small number of atoms make it to $|W\rangle$ before falling back to $|-\rangle$ via spontaneous emission. The rotated population is further reduced by the diminished mixing rate (see the dotted curve) due to the increased distance between the nodes. Moreover, the atoms climb a hill during the first half of the flight from Q to P', and fall down the hill with the same slope during the second half. Thus, there is very little net cooling or heating during this flight, and we approximate that all the cooling is due to the flight from P to Q.

To find the cooling coefficient ζ, we write the force as $F = -\zeta v$, and equate the work done on the atom to the energy loss in climbing the hill, to get $\zeta \cong (3\hbar k^2 \delta)/(2\pi\Gamma)$ for $\chi = \pi/4$. Finally, the velocity for which this cooling force is maximum is given by $v_c \tau_p = \chi/k$, so that $v_c \cong 0.3(g_0^2\Gamma)/(\delta^2 k)$ for $\chi = \pi/4$.

Figure 2 (thick line) shows a plot of the averaged force (in a system of units where $\hbar=1$, $k=1$, $\Gamma=1$) obtained from a continued fraction solution. The parameters used here are $\chi = \pi/4$, $g_0 = 0.3$, and $\delta = 1.0$. We fit this plot to a function of the form $f(v) = -\zeta_0 v/(1+v^2/v_c^2)$, which is maximum at $v = v_c$. We find $v_c \cong 5.5\times10^{-3}$ and $\zeta_0 \cong 0.81$. These results are to be compared with $v_c \cong 3.4\times10^{-3}$ and $\zeta_0 \cong 0.97$, as predicted by the Sisyphus model. Given the qualitative nature of the derivation, the agreement is reasonable. For equivalent values of parameters, these numbers are comparable ($\zeta_0 = 3.0$, $v_c = 4.0\times10^{-3}$) to the ones estimated by Dalibard and Cohen-Tannoudji [7] for a $J=\frac{1}{2} \leftrightarrow J'=\frac{3}{2}$ transition. The dashed line superimposed on Fig. 2 shows the corresponding values of the Doppler cooling force, with a slope smaller by about a factor of 30. We should point out that Mauri and Arimondo [3] reported a VSCPT scheme that is accompanied by Doppler precooling; therefore the resulting enhancement of VSCPT in their case would be much less than that achievable from polarization-gradient precooling.

In order to determine the equilibrium temperature of this system, it is necessary to determine the momentum diffusion coefficient D_P. The relevant part of the result is that, for $v=0$, we find $D_p = 0$ [10]. This is due to the

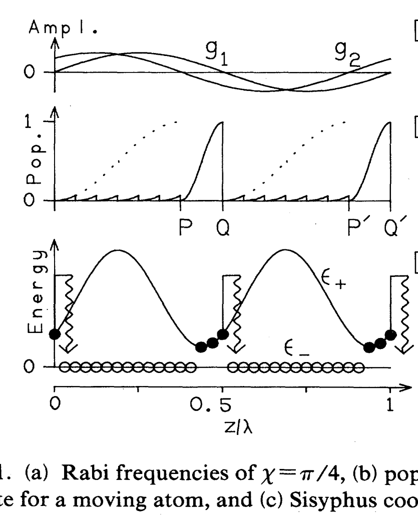

FIG. 1. (a) Rabi frequencies of $\chi = \pi/4$, (b) population of the $|W\rangle$ state for a moving atom, and (c) Sisyphus cooling.

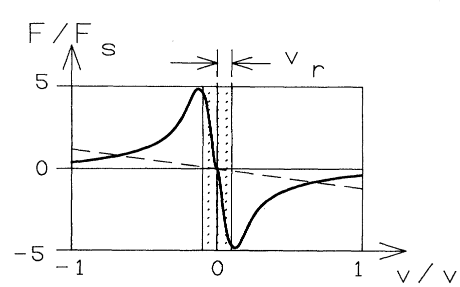

FIG. 2. The thick line shows the averaged polarization-gradient cooling force as a function of velocity, in units of $F_s = 10^{-3}\hbar k\Gamma/2$. Here, $v_d = \sqrt{\hbar\Gamma/m}$ and $v_r = \hbar k/m$, evaluated for sodium. The dashed line shows the corresponding Doppler cooling force, and the dotted area represents the capture range for VSCPT.

presence of a dark state [9,11],

$$|D\rangle \equiv [|a,-\hbar k\rangle \exp(-i\chi)+|a,\hbar k\rangle \exp(i\chi) - |b,-\hbar k\rangle - |b,\hbar k\rangle]/2\ , \quad (3)$$

which is decoupled from the state $|e,p\rangle$ for all values of p, where, for example, $|a,\hbar k\rangle$ represents an atom in state $|a\rangle$ with center-of-mass momentum of $\hbar k$. Thus $|D\rangle$ is a zero-velocity dark state. The system undergoes VSCPT into this zero-velocity dark state, so that the equilibrium temperature is limited by the interaction time only, and can be substantially below the recoil limit (ideally, the temperature approaches zero). Note that the dark state exists for all values of χ. On the other hand, the efficiency of VSCPT into this state varies [10] as $\sin^2\chi$. For the particular phases of $\chi=0$ and $\pi/2$, this result has been corroborated theoretically as well as experimentally by Aspect *et al.* [1,12].

The temperature of this system will become subrecoil as soon as significant VSCPT has taken place. The characteristic time τ_{vs} for this, however, is typically [1] much larger than that for polarization-gradient cooling τ_{pc}. As a result, for $t \ll \tau_{vs}$, the semiclassical picture of polarization-gradient cooling remains valid, and the system reaches a "partial-steady-state" temperature which can be larger than the recoil limit. This temperature is determined by the energy balance between the polarization-gradient cooling and the diffusive heating. However, since a large fraction of atoms are in the local $|-\rangle$ states during the polarization-gradient cooling process (see Fig. 1), even this transient diffusion is expected to be much smaller than that in the usual polarization-gradient cooling schemes. We therefore expect a precooled temperature that is much lower than the steady-state temperature in conventional schemes of polarization-gradient cooling.

In order to determine this partial-steady-state temperature and to investigate how this precooling enhances the rate of VSCPT, we have performed Monte Carlo simulations [13], treating the atom's external degree of freedom quantum mechanically. Figure 3 illustrates the results obtained for parameters close to those in Fig. 2. We start with a distribution of atoms that is flat over a momentum range of $\pm 10\hbar k$, as a rough approximation of a Gaussian distribution with an rms momentum of $10\hbar k$, corresponding to a Doppler precooled sample of sodium. The atoms that go beyond $\pm 15\hbar k$ are deemed too hot to be recaptured, and are considered lost. Figure 3(a) corresponds to the case where the lasers are on resonance ($\delta=0$), so that there is no cooling. However, VSCPT occurs, so that atoms start accumulating in the dark state, $|D\rangle$, manifested by the peaks at $\pm\hbar k$. The momentum redistribution takes place primarily by random walks, so that the atoms that are far from these peaks have a very low rate of getting into the dark state. Significant contributions to this accumulation come only from the atoms that are close to these peaks (i.e., within a distance of $\hbar k$, which we will call the VSCPT capture range). However, a large fraction of even these atoms get heated beyond the VSCPT capture range. As a result of these effects, we find that only a small fraction (about 5%) of the atoms

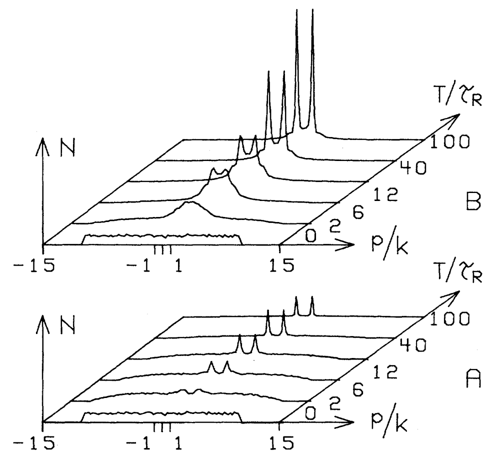

FIG. 3. (a) VSCPT in the absence of polarization-gradient cooling ($\delta=0$, and $g_0=0.3\sqrt{5/2}$) and (b) polarization-gradient cooling-assisted VSCPT, with $\delta=1$ and $g_0=0.3/\sqrt{2}$, corresponding to the same degree of saturation as in (a).

have accumulated in the dark state (within a momentum interval of $\pm\hbar k/8$) after $100\tau_R$, where $\tau_R \equiv 2m/\hbar k^2$ is the recoil time.

The result is much better when the laser is detuned, so that polarization-gradient cooling occurs along with VSCPT. This is illustrated in Fig. 3(b). The additional cooling helps in two ways. First, it precools the atoms, in about $6\tau_R$, to an rms momentum of $2\hbar k$. Note that this temperature is about a factor of 10 colder than the theoretical steady-state temperature in a one-dimensional polarization-gradient cooling using conventional schemes corresponding to an rms momentum of $6\hbar k$ [14]. Thus, most of the atoms are within the VSCPT capture range after the precooling. Next, as VSCPT proceeds, the atoms tend to get heated out of the capture range. However, the cooling force prevents them from getting too hot, essentially keeping them within the capture range all the time. As a result, we find that after the same amount time ($100\tau_R$), close to 40% of the atoms are in the dark state (a factor of 8 enhancement).

Before estimating the corresponding enhancement in three dimensions, we briefly point out how this scheme can be realized in three dimensions. It can be shown [9,10] that a three-dimensional dark state exists when a $J=1 \leftrightarrow J'=1$ transition is excited by opposite circularly polarized standing waves, with a pair in each of three orthogonal directions. The polarization-gradient cooling-assisted VSCPT is optimum when the standing-wave phase difference in each direction is $\pi/4$. In order to reconcile the facts that Doppler cooling requires positive detuning, while this polarization-gradient cooling requires positive detuning, one could employ several schemes. For example, a magneto-optic trap (MOT) can be used first to capture atoms from the background and cool them to the Doppler limit. Then the MOT can be turned off and the cooling scheme presented here can be turned on. In the time needed to go a factor of 4 below the recoil temperature (20 recoil times), only about 15% of the atoms would be lost [see Fig. 3(b)].

As in one dimension, the polarization-gradient precooling will keep all the atoms within a sphere of radius $2\hbar k$, which can be approximated by a cube of length $4\hbar k$ on each side. Let us now estimate the time needed for cooling the atoms to a factor of 4 below the recoil temperature, corresponding to a full width at half maximum of $\hbar k/2$ for each peak. In one dimension, this corresponds to accumulation of the atoms in two square wafers, each with a volume of $\frac{1}{2}\hbar k \times 4\hbar k \times 4\hbar k$, where each wafer contributes at least half of its population to the dark state. In three dimensions, this would correspond to accumulation in six cubes, each with a volume of $\frac{1}{2}\hbar k \times \frac{1}{2}\hbar k \times \frac{1}{2}\hbar k$, where each cube contributes at least one-sixth of its population to the dark state. Since VSCPT takes place via a random walk in momentum space, the rate of 3D VSCPT is smaller than that of 1D VSCPT simply by the weighted ratio of these two volumes, which evaluates to 64. In one dimension the time needed for reaching this temperature is about $20\tau_R$; 3D cooling should take $1280\tau_R$, which is about 8 msec for sodium.

Note that this factor is given by the square of the momentum width of the precooled atoms (in units of the desired final momentum width), and is therefore proportional to precooled temperature. In the absence of polarization-gradient precooling, the factor would be 25 times larger (since the precooled temperature is 25 times lower than the Doppler temperature). In addition, recall that in 1D, regular VSCPT is about a factor of 8 less efficient than the polarization-gradient cooling-assisted VSCPT (see Fig. 3). Thus this scheme would be about a factor of 200 more efficient than regular VSCPT in three dimensions.

In summary, we show that polarization-gradient cooling occurs in the Λ system simultaneously with VSCPT. This process may continuously and efficiently transfer atoms from a Doppler temperature sample to near-recoil velocities that are within the capture range of VSCPT, which would then continuously cool the atoms to below the recoil limit. For sodium, this polarization-gradient precooling and confinement is estimated to enhance the VSCPT pumping rate by more than two orders of magnitude compared to the rate achievable from Doppler precooling alone. We estimate, for example, that this scheme would cool sodium atoms in three dimensions to one-fourth the recoil temperature in 8 msec. Experimental efforts are in progress for realizing this scheme in three dimensions.

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