Bichromatic Laser Cooling in a Three-Level System

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We report a 1D study of optical forces on atoms in a two-frequency laser field. The light couples two ground state hyperfine structure levels to a common excited state of ^{85}Rb, thus forming a Λ system. We observe a new type of sub-Doppler cooling with blue-tuned light that uses neither polarization gradients nor magnetic fields, efficient heating with red tuning, and the spatial phase dependence of these. We observed deflection from a rectified dipole force and determined its velocity dependence and capture range. We report velocity selective resonances associated with Raman transitions. A simplified semiclassical calculation agrees qualitatively with our measurements.

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All sub-Doppler laser cooling (SDLC) methods can be characterized by a damping force derived from a spatially varying light field (e.g., from superposition of two counterpropagating laser beams) [1,2]. In all cases studied to date, motion of the atoms prevents their internal state distribution from reaching steady state. Deviation from the steady state is countered by the irreversible process of optical pumping (spontaneous emission) that tends to restore the steady state distribution. The time lag of this process leads to nonadiabatic response of moving atoms to the standing wave field, and, under suitable conditions, a velocity dependent damping force. In the past polarization gradients [1,2] or magnetic fields [3] were used to create the spatial dependence of the atomic steady state. In this Letter we report a new SDLC scheme that requires neither polarization gradients nor magnetic fields. Our two-frequency experiments can produce a rectified optical force, and we report here the study of the velocity dependence of such forces. All our measurements agree well with the numerical results from a semiclassical model.

Our new scheme employs two standing waves with the same linear polarization but different laser frequencies, ω_1 and ω_2, corresponding to excitation of the two ground state hyperfine levels of ^{85}Rb (separated by $\omega_{\rm hfs}\cong 2\pi \times 3.036$ GHz). When ω_1, ω_2, and $\delta\equiv(\omega_2-\omega_1)-\omega_{\rm hfs}$ are properly chosen, the time lag described above can also damp the motion of moving atoms because of the nonadiabatic response of the populations of levels $|1\rangle$ and $|2\rangle$. Recently there has been considerable theoretical interest in the optical forces on three level atoms with such a Λ configuration of levels [4–13] but only two experiments [14,15].

SDLC is often described in a picture called Sisyphus cooling (because of the close analogy with a Greek myth [16]) where atoms lose kinetic energy when they move in the potentials caused by the light shifts of the laser field. Such descriptions exist at low intensity for the steady state processes of polarization gradient [1,16,17] and magnetically induced cooling [3], as well as transient laser cooling processes [18]. With two frequencies present, a similar energy loss or Sisyphus picture is appropriate when the relative spatial phase of the standing waves is considered.

Consider the case where the intensity maxima of the standing wave at ω_1 correspond to the minima of ω_2 as shown in Fig. 1(a), and both ω_i's are larger than the corresponding atomic resonance frequencies as shown in Fig. 1(b). The light shift of each ground state sublevel $|i\rangle$ is dominated by the nearly resonant frequency ω_i, and hence is positive. Atoms moving through the node of ω_1 are optically pumped to $|1\rangle$ and must increase their potential energy to move further as shown in Fig. 1(a). This comes at the expense of their kinetic energy, and they slow down as they approach the top of the potential hill at the antinode of ω_1. However, they are most likely to be optically pumped to $|2\rangle$ at a point where the intensity of light at ω_1 is high, and then they begin climbing another hill. Repetition of this process rapidly converts kinetic energy into potential energy which is then dissipated into the fluorescent light of the spontaneous decays, and atoms are cooled. This process obviously produces heating if the two frequencies are red of resonance thereby producing negative light shifts, and its effectiveness is

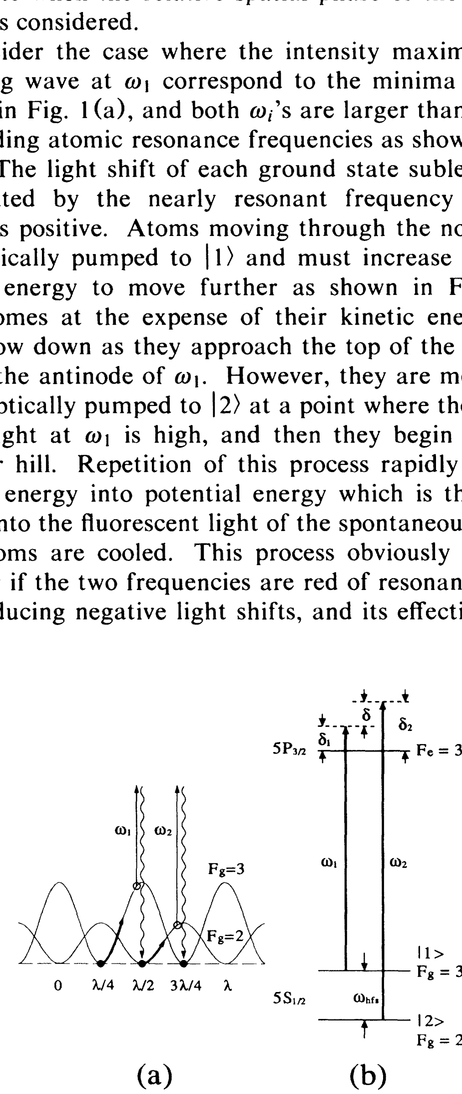

FIG. 1. (a) The spatial dependence of the unequal light shifts (caused by either different transition strengths or different light intensities) near the two frequencies ω_1 and ω_2. (b) The atomic levels and definitions of the δ's.

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compromised when the standing wave phase difference is different from π.

Most of our experimental setup has been described in previous work [3,17,18] and is only briefly described here. Rb atoms emerge from a 150 °C oven with a horizontal slit aperture 0.06 mm high by 2 mm wide. A horizontal atomic beam is formed by a vertical slit 2 mm high by 0.06 mm wide, 35 cm away from the oven. The atomic beam is crossed at 90° just after the second slit by a laser beam containing two frequencies that is retroreflected by a movable mirror to form two horizontal standing waves with the same polarization but different frequencies. The transit time of atoms with the average velocity 350 m/s in the 23 mm long by 5 mm high laser beam is about 65 μs. The Earth's magnetic field is carefully canceled to less than 10 mG by square Helmholtz coils. We measure the atomic beam profile parallel to the direction of the optical **k** vectors with a scanning hot platinum-tungsten wire, 25 μm in diameter, 1.3 m away from the interaction region.

Linearly polarized light from a 35 mW Sharp model LTO25 diode laser is split into two beams, and the weaker one passes through an 80 MHz acoustic-optical modulator and then to a Rb vapor cell. A crossover resonance in the saturated absorption signal is used to lock the laser near the $F=3\rightarrow 3$ transition in ^{85}Rb near $\lambda=780$ nm, and facilitates tuning on either side of the atomic resonance. About 10^{-5} of the stronger beam is fed back to the laser by a blazed grating to reduce the spectral width to ~ 1 MHz. The two frequencies are generated by passing the light through an electro-optic modulator (EOM) [19]. A mechanical shutter interrupts this beam, and many systematic effects have been eliminated by subtracting laser beam off from laser on measurements.

The spatial phase difference between the two light shift potentials is of paramount importance in this experiment. The standing waves of the two frequencies have nodes at the surface of the retroreflecting mirror, but their relative phase $\Phi=2z(\omega_1-\omega_2)/c$ varies with distance z from the mirror because of their frequency difference; for $\omega_1-\omega_2\cong 2\pi\times 3$ GHz the spatial period of this variation is $\cong 5$ cm. Since this is much larger than the 0.06 mm atomic beam diameter, atoms see a fixed value of the phase between the standing waves. This can be varied by translation of the retroreflecting mirror.

Figure 2(a) shows the results of our measurements of SDLC using two optical frequency standing waves for the case of $\Phi=\pi$ (optimum cooling) and $\Phi=0$ obtained by moving the retroreflecting mirror about 2.5 cm. Even at $\Phi=0$ there is a significant signal of cooled atoms, but this arises from two additional cooling mechanisms operating in this experiment. First, the atomic coherences produced by stimulated Raman transitions between the states $|1\rangle$ and $|2\rangle$ for $\delta=0$, neglected in this Sisyphus description, produce velocity selective resonances (VSR) at $v=0$ as described below. Second, for the $F=3\rightarrow 3$ transition driven by linearly polarized light, the excitation of the

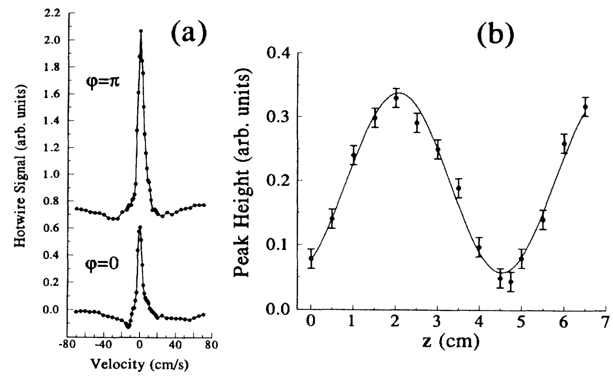

FIG. 2. (a) The measured atomic beam profile for $\Phi=0$ and π. Here $\delta_1=\delta_2\cong+6$ MHz ($\delta=0$) and the intensities $I_1\cong 3.2$ mW/cm^2 and $I_2\cong 1.6$ mW/cm^2 ($\cong I_{sat}\equiv\pi hc/3\lambda^3\tau$). A change of 1.0 on the vertical axis corresponds to a 100% change of the signal. (b) How the measured central peak height at large δ varies with Φ. The solid line is a fit of a sine wave to the data whose phase is within ± 0.5 cm of our measurement.

$M_F=0$ sublevel is forbidden, and transient cooling into this dark state contributes to this residual cooling [18].

We have tested that this residual peak of cold atoms is mostly the result of transient cooling by varying the interaction time with an aperture on the laser beams. We found that it is produced in a time comparable to the optical pumping time $1/\gamma_p$. For this test we used a large enough value of δ so that the VSR peaks are well resolved from the $v=0$ signal (see below), and the remaining signal at $\Phi=0$ is only from transient cooling. Figure 2(b) shows the Φ dependence of the height of the cooled atom peak at $v=0$ with large δ.

The Sisyphus description of these experiments given above is limited because it is based only on the populations of states, and neglects coherences that are associated with Raman processes between the two long lived ground states. It is well known that these coherences have important effects on the damping forces, and in previous experiments we have shown that damping to $v=0$ [20] and to finite velocities [20,21] depends on Raman resonances between Zeeman shifted states that redistribute light between counterpropagating beams. These VSR are always present in all known cases of steady state SDLC [22,23].

The direct analog of the magnetic VSR can be seen with two laser frequencies when $\delta\equiv(\omega_2-\omega_1)-\omega_{hfs}\neq 0$ [20]. Then the condition for VSR is satisfied at the resonance velocity $v_r=\pm\delta/2k$. Figure 3(a) shows the measured atomic beam profiles for different values of δ and Fig. 3(b) shows the velocity associated with the side peaks of Fig. 3(a) vs δ. Two side peaks appear for each value of δ because atoms at the resonance velocity v_r can absorb either ω_1 or ω_2 from either direction of the laser beam, depending on the sign of their velocity. Of course,

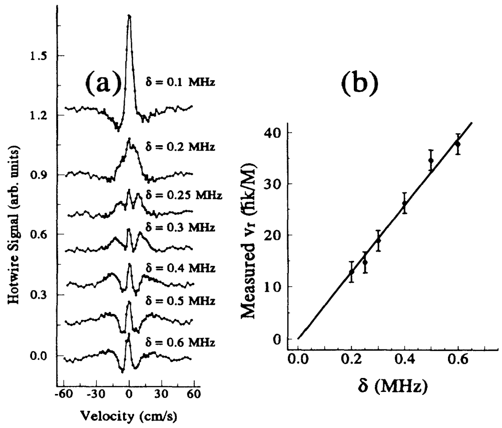

FIG. 3. (a) The measured atomic beam profile for various values of δ that produce VSR at velocities $\pm\delta/2k$. A change of 1.0 on the vertical axis corresponds to a 100% change of the signal. (b) The measured resonant velocities of the peaks vs δ. The straight line is a plot of $v=\delta/2k$. The laser intensity is $(0.6)I_{sat}\cong 1$ mW/cm^2 for each beam and $\delta_1\cong 10$ MHz.

stimulated emission into the other beam completes the Raman transition.

The widths of the $v\neq 0$ peaks, Δv, are limited by the width of the longitudinal velocity distribution Δv_l through $\Delta v/v \sim \Delta v_l/v_l \sim 1/2$ for a thermal beam, and their widths are indeed about half their distances from the $v=0$ peak. They begin to merge into it when their velocity is ~ 20 cm/s, corresponding to $\delta\cong 0.25$ MHz. It must be emphasized that the widths of these peaks are all below the Doppler limit (10 cm/s): atoms undergo SDLC to the velocity v_r.

Up to this point we have considered only the special cases $\Phi=0$ or π, and the same sign for the detuning $\delta_i\equiv\omega_i-\omega_{atom(i)}$ of the two individual laser frequencies (see Fig. 1). We now consider cases where these conditions are relaxed. In addition to SDLC, we show that various values of δ_1 and δ_2 can produce qualitatively new effects. In particular, when δ_1 and δ_2 have opposite signs, the light shifts for the two ground states $|1\rangle$ and $|2\rangle$ are opposite. For $\Phi=0$ or π, partial cancellation of the kinetic energy change when the atoms move on these oppositely light shifted potentials severely reduces the heating or cooling forces, but for other values of Φ this cancellation is less complete, and there remains a "rectified" dipole force [11,13,14,24,25].

Figure 4 shows schematically how this works if we choose for simplicity equal probability for the optical pumping process $|1\rangle\to|2\rangle$ and $|2\rangle\to|1\rangle$. Atoms are optically pumped between the two ground states, but spend most of their time in the state with the lowest standing wave intensity as shown by the heavy lines in Fig. 4. The vertical arrows in Fig. 4 show where these states exchange roles. For velocity v small enough so that the average optical pumping time $1/\gamma_p$ is less than $\Delta z/v$,

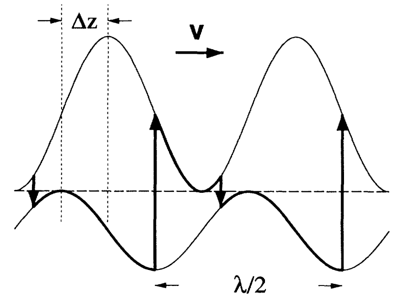

FIG. 4. The spatial dependence of the light shifts for δ_1 and δ_2 with opposite signs and Φ different from 0 or π. The arrows show the position and the direction of optical pumping between states $|1\rangle$ and $|2\rangle$. Atoms travel along the thickened lines to the right, and, for the case shown, the average force is clearly to the right. For motion to the left, the force is still to the right.

where Δz is the standing wave displacement, then the optical force has a fixed direction independent of velocity when averaged over a wavelength. This can be understood from the average slope of the potential curve indicated by the heavy line in Fig. 4 where atoms spend most of their time. This average does not change sign for small lateral displacements of the heavy line in either direction, corresponding to velocity changes. We therefore expect a maximum force near $v=0$, with the same sign for $v<0$ or $v>0$ [13]. The force should decrease with a velocity width $\sim\gamma_p\Delta z\cong\gamma_p/k$.

In our experiment the atoms emerge from the second slit in a velocity range of $\sim\pm 1$ m/s, much larger than the "capture range" γ_p/k of ~ 10 cm/s. Atoms with a large transverse velocity are thus unaffected by the deflection force, while slower atoms undergo a deflection to the right or left depending on the sign of Δz. Changing the sign of Δz can be accomplished either by exchanging the signs of the δ_i's or by moving the retroreflection mirror, and we have done both. The data of Figs. 5(a) and 5(b) clearly show such deflections of the atoms for opposite signs of Δz, and also provide a measure of the effective velocity range for this rectified force.

We have done semiclassical calculations of the force on moving atoms, starting with the optical Bloch equations to find the density matrix. Using only the transfer of population between states $|1\rangle$ and $|2\rangle$, and neglecting any coherences that may be produced in the optical excitation, we have calculated the force for the many experiments described above. For the parameters of Fig. 2 we find the usual dispersion-shaped velocity dependence of the force with strength and capture range that produce SDLC as shown in our measurements. For the parameters of Figs. 5(a) and 5(b), we show in Figs. 5(c) and 5(d) the anticipated single peak (or dip) in the force vs velocity curve, with no zero crossing and a width $\sim\gamma_p/k$. Such model calculations cannot be used for the data of Fig. 3 because the VSR arise from coherences that are

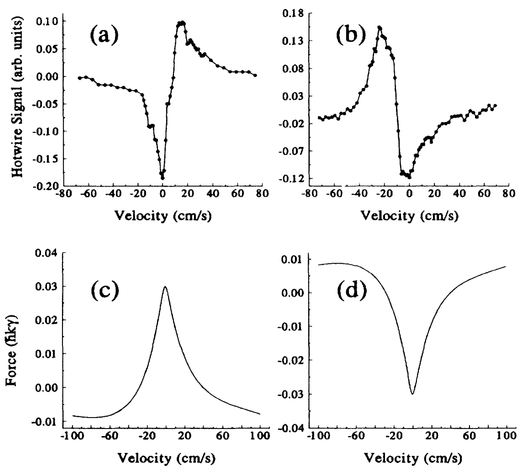

FIG. 5. (a),(b) The measured spatial profile of the deflected atomic beam for two different signs of the δ_i's for $\Phi = \pi/4$. A change of 1.0 on the vertical axis corresponds to a 100% change of the signal. Similar results are obtained by moving the retroreflecting mirror. The limit of velocity capture range is evident in the data. (c),(d) The calculated force curves for $\Phi = \pi/4$. The laser intensity is $\cong 1.6$ mW/cm^2 for all parts, $\delta_1 = +6$ MHz and $\delta_2 = -3$ MHz for (a) and (c), and $\delta_1 = -3$ MHz and $\delta_2 = +6$ MHz for (b) and (d).

not included. We plan to extend the semiclassical methods we have developed, that include the multiple magnetic sublevels [22,23], to two frequencies to model these experiments.

Cooling atoms with two frequencies is a fundamentally new SDLC scheme that requires neither polarization gradients nor magnetic fields. Its damping, maximum force, capture range, and diffusion are comparable to those of many previously studied SDLC schemes such as polarization gradients [1,2] and magnetically induced laser cooling [3]. However, there are additional free parameters that provide flexibility for further study of SDLC processes. These are the detunings δ_1 and δ_2, saturation parameters s_1 and s_2, and the phase between the standing waves Φ. It also provides a better insight into particular interpretations of SDLC such as the Sisyphus picture. The velocity dependence of the topical rectification force is an important new area for further detailed study to test our understanding of the two color processes, and to provide for new methods of optical control of atomic motion. We plan to extend our study of this system to include polarization differences between the two beams, polarization gradients of each beam, and the effect of magnetic fields.

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