PHYSICAL REVIEW A VOLUME 60, NUMBER 3 SEPTEMBER 1999

Measurement of the bichromatic optical force on Rb atoms

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(Received 5 May 1999)

The limit of $\hbar k\gamma/2$ imposed on the magnitude of radiative forces by the spontaneous decay rate γ of the excited state can be overcome by coherent control of the momentum exchange between atoms and the light field. This can be implemented with two light beams, each containing two frequencies whose phases, amplitudes, and frequency difference are carefully chosen. We have made precise measurements of the extremely large magnitude and velocity range of this bichromatic force, and have shown that its velocity dependence near the edge of its range is suitable for atomic beam slowing and laser cooling. Our measurements have corroborated various models and calculations of this bichromatic force. [S1050-2947(99)51009-3]

PACS number(s): 32.80.Pj, 42.50.Vk

This paper reports careful measurements of the velocity-dependent bichromatic force that is usable for slowing atomic beams and cooling atoms. It is distinguished from the radiative forces used for laser cooling for the past 20 years by both its huge magnitude F_b and velocity range v_b. We have measured F_b to be $\cong$ five times larger than the maximum possible values of the radiative force. Furthermore, the factor of 5 is imposed only by our laser power: this bichromatic force has no simple, fundamental limit to either F_b or v_b.

We have made extensive measurements of $F_b(v)$ to $\pm 5\%$. We deflected Rb atoms from a thermal beam using a wide range of laser parameters, and our results show that the bichromatic force is a most useful and important tool for the production of cold, dense atomic samples for traps, lithography, and other uses. Our measurements support calculations that include the π-pulse model [1,2], dressed atom pictures [3,4], and direct numerical integration of the optical Bloch equations (OBE's) [5].

In the early days of laser cooling, the view of two-level atoms moving in a monochromatic laser beam provided the fundamental picture. In such Doppler cooling, both the slowing force *and* the dissipation are provided by the incoherent sequence of absorption followed by spontaneous emission, and are thus limited by the natural linewidth $\gamma \equiv 1/\tau$. Sub-Doppler cooling forces are similarly limited to a magnitude of $\hbar k\gamma/2$, where $k \equiv 2\pi/\lambda$ and λ is the wavelength of the transition. In contrast to this radiative force, the dipole force arises from absorption from one light beam, followed by stimulated emission into another, and does not suffer from such limits, but its spatial average usually vanishes. In 1989 there were two independent proposals that used two frequencies to provide spatial rectification of the dipole force [1,6].

Unlike the limited velocity range of the rectified dipole force, the bichromatic force described here has both a very large v_b *and* F_b. It arises from the coherent control of the momentum exchange between the atom and the laser fields associated with a long sequence of rapid absorption—stimulated emission cycles. This is interrupted by relatively infrequent spontaneous emissions at the natural decay rate γ, which act to enable the dissipative aspect. The bichromatic force $F_b(v)$ not only covers a broad velocity range v_b, but also has a strong velocity dependence at its range boundaries so that it can cool. Thus it is a valuable tool for fast, short-distance deceleration of thermal atoms, thereby minimizing atom loss.

Recently the bichromatic force was used for atomic beam slowing [2]. With only modest laser power and no Doppler compensation, these authors decelerated a thermal beam of Cs to ~ 20 m/s in just a few centimeters. Their intuitive π-pulse model of the force considers atomic motion along the axis of the light beams. Each beam contains the two frequencies $\omega \pm \delta$, detuned from atomic resonance by $\pm\delta$ (difference $= 2\delta$). As an amplitude-modulated single carrier frequency at the atomic resonance ω_a, the modulation period is π/δ, and δ satisfies $\pi/\delta \ll \tau$. Their equal intensities are chosen so that one ''pulse'' of the beat envelope is a π pulse: ground-state atoms are coherently driven to the excited state and vice versa. This condition is $\Omega = \pi\delta/4$, where $\Omega \equiv \gamma\sqrt{I/2I_s}$ is the on-resonance Rabi frequency of each frequency component of each beam and the saturation intensity $I_s \equiv \pi hc/(3\lambda^3\tau)$.

Since atoms are subject to these coherent π pulses alternately from one side and then the other, the force on them can become very large. This is because the first π pulse causes excitation and momentum transfer $\hbar k$ in one direction, and the second π pulse, in the opposite direction, causes stimulated emission with a momentum transfer along the same direction as the first pulse. Similar forces have been demonstrated using picosecond π pulses on Cs [7]. Thus the optimum total force is given by $2\hbar k\delta/\pi$, much larger than the maximum radiative force $\hbar k\gamma/2$, because it is a controlled, rapid momentum exchange. The result of spontaneous emission and its concomitant decoherence yields an average force that is $\hbar k\delta/\pi$, half the optimum estimated above, and this is borne out by the numerical calculations of Refs. [2,5,8]. Our measurements corroborate the magnitude of the force from both this estimate and the numerical calculations.

The numerically calculated $F_b(v)$ plotted in Fig. 1 for various values of the ratio Ω/δ is characteristic of the bichromatic force. The general progression shown in the various panels of Fig. 1 is unchanged even with variations of δ/γ and Ω/γ. These calculations were done by direct numerical integration of the OBE's using the program kindly provided by the authors of Refs. [2,5]. Figure 1 also shows

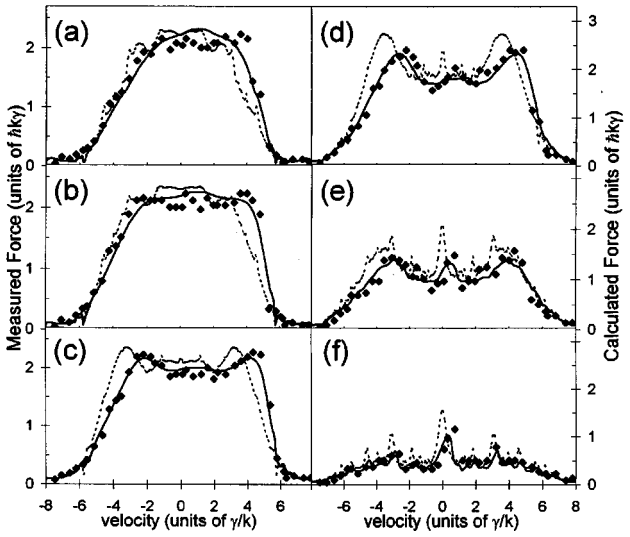

FIG. 1. Each panel shows the velocity dependence of the bichromatic force calculated for a relative phase of 95° by direct numerical integration of the OBE's (dotted line), the calculated value convolved with the experimental resolution (solid line), and the measured values (data points). For these data we used $\delta = 2\pi \times 55$ MHz $= 9.1\gamma$. The ratios of the different values of Ω were chosen by a half-wave plate and polarizer combination, starting with the maximum value in (a) of 10.8γ, and decreasing by the factors 0.95 in (b), 0.90 in (c), 0.83 in (d), 0.74 in (e), and 0.64 in (f) from Ω_{max}. The calculation and experiment have vertical scales different by the factor 0.83 in all panels. Note that panel (f) corresponds to the π-pulse condition $\Omega = \pi\delta/4$.

that $F_b(v)$ spans approximately $\pm\delta/2k$. It is sometimes desirable to arrange for the force to act from $v = \delta/k \equiv v_b$ to $v = 0$, and this is readily implemented by upshifting both of the frequencies in one of the counterpropagating beams and downshifting those in the other beam [2]. If the shifts are $\pm\delta/2$, the picture given above is correct in a frame moving at speed $v_b/2$ in the laboratory, which shifts the horizontal axis of Fig. 1 by the desired amount. However, this results in the requirement for four distinct laboratory frequencies.

Within the framework of the model above, F_b and v_b scale together, and thus the time required to change atomic velocities by v_b is independent of δ. More generally, the time t_b required to change velocities by a fixed fraction $\eta \leqslant 1$ of v_b is $t_b = \eta(Mv_b/F_b) = \pi\eta/2\omega_r$, where $\omega_r \equiv \hbar k^2/2M$ is the recoil frequency. For the Rb transition at $\lambda = 780$ nm, where $\omega_r \approx 2\pi \times 3.8$ kHz, $t_b \approx 60\eta$ μs. Thus a typical thermal Rb atomic beam at 300 m/s can be brought to rest in less than 1 cm.

The required light intensity I can be estimated from v_b using $\Omega \simeq \delta$. Then $I \equiv 2(\Omega/\gamma)^2 I_s \simeq 2(\delta/\gamma)^2 I_s$, where $I_s \simeq 1.67$ mW/cm^2 for the Rb transition we use. Thus the required power can be determined from v_b appropriate to an experiment and the geometrical conditions that determine the laser beam size.

The relative phase of the ''pulses'' of the counterpropagating light beams is determined by the distance from the atomic beam to the retroreflecting mirror resulting in F_b, as shown in Fig. 2. The atoms are subject to the bichromatic force whose magnitude is determined by their transverse velocity (see Fig. 1) for a time interval dependent on their

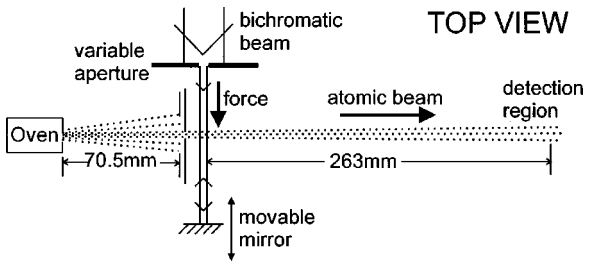

FIG. 2. Atoms emerge from the oven at the left, are vertically collimated by the wide horizontal slit, and then well collimated by the 190-μm vertical slit. In the interaction region they cross the laser beams that exert the bichromatic force in the direction shown by the arrow for about 6 mm, and then they fly freely to the detection region.

longitudinal velocity and the laser beam width. We measured the displacement and the time of flight of the atoms, from which we calculated their deflection angle and thus the average force on them. The competition between readily measurable deflection and suitable resolution of the force led to the choice $\eta = 0.25$, but we have varied it from 0.04 to 0.4.

An overall top view of our apparatus is shown in Fig. 2. The beam from an oven aperture of diameter 330 μm is vertically collimated by an LN_2-cooled, 800-μm high horizontal slit 70.5 mm away, and then by a 190-μm-wide vertical slit that is 3 mm from this horizontal slit. This vertical slit can be moved by 20 mm to choose various transverse directions, resulting in a transverse velocity resolution of $\simeq \pm 0.5$ m/s. About 8 mm beyond the vertical slit the atoms enter an interaction region where the Earth's field is cancelled to ± 3 μT, and can be varied to ± 300 μT in any direction. The length of this interaction region d is typically limited to the central 6 mm of the expanded bichromatic laser beams where their intensities are quite uniform [$2\times$ (beam waist) $= 18$ mm].

The light field is produced by a Ti:sapphire laser detuned to drive the $(F, M_F) = (2,2) \rightarrow (3,3)$ transition in ^{87}Rb and the $(3,3) \rightarrow (4,4)$ transition in ^{85}Rb. (For ^{85}Rb, the beam passes through a 2.9-GHz electro-optic modulator (EOM) to impose a weak hfs repumping frequency on it. The other EOM sideband is ignored). The beam is then incident on an acousto-optic modulator (AOM), as shown in Fig. 3. The incoming laser beam at frequency ω_ℓ is 50% diffracted into an outgoing beam at $\omega_\ell + \delta$, while the rest is at ω_ℓ. Both

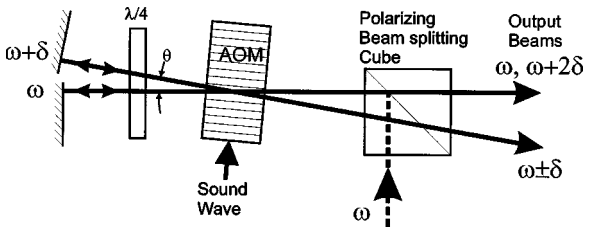

FIG. 3. The laser beam enters the AOM and is Bragg diffracted with 50% efficiency into an outgoing beam. The emerging beams have equal power and frequencies $\omega_\ell + \delta$ and ω_ℓ. Both are retroreflected back to the AOM, and it splits each of them again, producing beams as shown (the quarter-wave plate and polarizing beam splitter serve to extract the two final beams). With $\delta = 2\pi \times 55$ MHz, θ is ≈ 12 mrad.

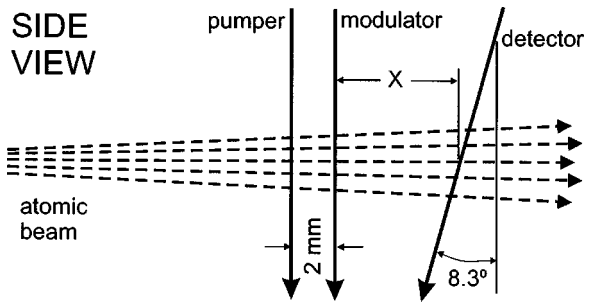

FIG. 4. The three lasers used for longitudinal velocity-selective detection of ^{87}Rb (^{85}Rb). The pumper is used only for ^{85}Rb and is tuned from the $F_g=2\rightarrow F_e=3$ transition to optically pump all the atoms into the $F_g=3$ hfs ground state. The modulator is modulated at 3 kHz by >100 MHz and is tuned near the $F_g=2(3)\rightarrow F_e=1(2)$ transition to empty the $F_g=2(3)$ state. The detector is tuned to the $F_g=2(3)\rightarrow F_e=3(4)$ cycling transition. The inconsequential distance x varies linearly between 2 and 12 mm (due to the three-dimensional detection geometry) as the detector beam is transversely scanned.

beams are retroreflected and thus split again by the AOM, producing beams as shown. We have used each pair of these beams as the bichromatic beam (using the retroreflector) or both pairs in a counterpropagating configuration. [These four laboratory-frame frequencies exactly satisfy the criteria for a bichromatic force in a frame moving at $v=(\omega_a-\omega_{\not/})/k$. For our choice of $\omega_a-\omega_{\not/}=\delta/2$, the force ranges from $v=v_b$ to $v=0$, precisely what is needed for beam slowing or collimation.]

After the interaction region the atoms fly freely for $D=26.3$ cm, and then their horizontal positions are measured by optical absorption in the detection region. Here the ^{87}Rb (^{85}Rb) atoms are subject to two (three) separate laser beams as shown in Fig. 4. The first beam, the ''pumper,'' is used only for ^{85}Rb. It is vertical and is tuned to the $F_g=2\rightarrow F_e=3$ transition to optically pump the atoms into the $F_g=3$ hfs ground-state sublevel. The second one, the ''modulator,'' is tuned near the $F_g=2(3)\rightarrow F_e=1(2)$ transition to empty the $F_g=2(3)$ state, and its frequency is modulated by >100 MHz at 3 kHz to temporally modulate the population of the $F_g=2(3)$ state to enable lock-in detection. The third one, the ''detector,'' is directed at 98.3° to the atomic-beam axis for velocity selection. A large lens directs the detection laser beam onto a photocell from any position in its scan range. All three laser beams are spatially scanned across the atomic beam by an oscillating mirror to map out the atomic beam's spatial profile (see Fig. 4).

The geometry fixes the width of the atomic beam at this point at 1 mm, and the detection laser beam is a 510-μm-wide image of a slit. The accessible width of the detection region is 8 cm, making more than 50 spatial regions or transverse velocity steps available, spanning a total angle of $\simeq\pm 0.1$ rad. The longitudinal velocity is selectable by the frequency of the detection laser at an 8.3° angle; our experiments span the range of 250—400 m/s. The power broadened width from the detection laser is about 10 MHz. Including the spread of vertical velocities, the resulting longitudinal velocity resolution is ± 30 m/s. Thus the interaction time spread ranges from $\cong 15\%$ to $\cong 25\%$, with a central uncertainty $<5\%$.

Atoms experience a transverse bichromatic force over a distance d fixed by apertures on the laser beams (typically $d\cong 6$ mm). We have accounted for the diffraction of these apertures, but it is quite small. The longitudinal velocity group selected by the detection laser determines the interaction time, and the absolute longitudinal velocity is calibrated by an optical pumping–time-of-flight method to about $\pm 0.7\%$. The transverse velocity change caused by the bichromatic force is determined from the physical shift Δx in the horizontal position of the absorption peak that is measured by the spatially scanned detection laser. The velocity change is used to infer the force whose velocity dependence is plotted in Fig. 1 (points). Also plotted (line) is the theory that has been convolved with the experimental resolution. The solid lines and the measurements are shifted to the right and show a small asymmetry because the results are plotted versus the initial velocity, and each single measurement necessarily spans a range of a few m/s to achieve sufficient displacement. Ω_{max} is the only free parameter in the theory, and it is chosen to best match the shape and magnitude trends of the data. This agrees within a few percent of the measured intensity.

The measured force is consistently smaller than the calculated one, so a scaling factor has been used between the vertical axes on each side of Fig. 1 for the best match. We found this factor to be 0.83 ± 0.02 for ^{85}Rb (plotted in Fig. 1) and 0.79 ± 0.02 for ^{87}Rb. An isotopic difference could be caused by variations in the optical pumping among the Zeeman and hfs levels of the two isotopes. For the ^{87}Rb data we do no hfs optical pumping because its larger hfs allows adequate spectroscopic resolution. Thus the ^{87}Rb measurements were done on only those atoms that emerged from the source in the $(F,M_F)=(2,2)$ sublevel, or were optically pumped very quickly in the circularly polarized bichromatic light, and remained there throughout the interaction region. By contrast, the ^{85}Rb measurements were done in the presence of the continuous repumping light produced by one of the sidebands of the EOMs discussed above.

Figure 1 shows detailed agreement between the data and the characteristic progression of the calculated force curves as Ω is varied, confirming that the intensity measurements are correct. That is, the frequency δ is known, so the plots of Fig. 1 provide a direct comparison between Ω and δ that is consistent with our measurements. The measurements have covered a wide range of parameters, and constitute many independent checks to test our calculations of the force. Some of these are:

(i) The measured force is calculated from $F_{meas}=Mv_{\not/}^2(\Delta x)/Dd$, where $v_{\not/}$ is the selected longitudinal velocity. Thus F_{meas} depends only on three measured distances and $v_{\not/}^2$, and does not depend on quantities that are more difficult to determine such as the Rabi frequency Ω.

(ii) We used a single-frequency, high-intensity deflecting laser beam to produce a force of $\hbar k\gamma/2$ that provides a direct atomic force calibration accurate to $\pm 5\%$.

(iii) We found that the data were better fitted with phase shifts 5° larger than those determined by the distance to the retromirror. At least two factors act to shift the phase from this value. The first is the additional path length through the 1-cm-thick window, which adds $\approx 1°$ to the phase. The second arises from the dispersion of the residual Rb vapor in the

atomic beam chamber that acts to reduce the phase. This dispersion effect was tested in two ways: (a) Using a small Michelson interferometer with a Rb absorption cell in one arm, we scanned a diode laser through the Rb resonance and measured the fringe shift. (b) We calculated that a $-4°$ shift along the 20-cm round-trip path between the atomic beam and the exit window can be caused by a Rb vapor pressure of 3.4×10^{-8} Torr ($\sim$1/10 of the room temperature vapor pressure). This seems reasonable in our vacuum.

(iv) Our measurements used various intensities, polarizations, applied magnetic fields, AOM frequencies, and phases of the bichromatic ''beats.'' We even reversed the force by changing this phase by 180°. The entire mass of data shows the detailed features of the velocity dependence calculated numerically. We have also done extensive measurements with four frequencies, and again have found agreement to a comparable level of accuracy.

(v) We have made measurements on ^{87}Rb (using no repumper) to check the effects of optical pumping, and found essentially no difference from the ^{85}Rb data. The signal-to-noise ratio was worse because we used only that small fraction of the oven output that was in the $(F,M_F)=(2,2)$ sublevel of this less abundant isotope.

We feel that the discrepancy between F_{meas} and the calculated forces of about 20% is caused by a number of small contributions. Clearly one of these arises from the readily visible effects of atmospheric turbulence on the laser beam that travels 15 m through a pipe from the laser table to the AOM (a fiber is impractical because of the power loss). When we choose the best Ω_{max} to fit the data, it represents some average value. The turbulence causes fluctuations that differ for the two frequencies of the bichromatic laser beam. This creates an intensity mismatch of the beams that can only lower the force.

Another beam intensity effect arises from the loss of light associated with the imperfect transmission of the window traversed twice by the retroreflected beam. This not only produces a loss of a few percent, but also exposes the atoms to light of a different phase shift than that of the main beam. In addition, absorption by the residual cloud of Rb vapor mentioned above further unbalances the counterpropagating beams. Each of these independently can reduce the measured force by a few percent.

Still another effect arises from optical pumping. In the case of ^{87}Rb, where we use no repumper and lose those atoms that fall into the $F=1$ ground state, there is still an initial optical pumping among the Zeeman levels as the atoms enter the circularly polarized bichromatic laser beams. In the case of ^{85}Rb, where optical pumping occurs (there is almost no signal without the repumper), the atoms still spend some of their time in the $F=2$ ground state where they experience no force.

To conclude, we have performed careful and detailed measurements of the bichromatic force. With our parameters, we have found it to be more than five times the magnitude of the Doppler force and to have velocity-dependent details that agree extremely well with calculations. Because of its potential for a huge magnitude and velocity range, along with the strong velocity dependence at the range boundaries, this force will enable atomic-beam slowing and cooling in a new domain of parameters. It is particularly well suited for decelerating metastable $^3S_1$ He atoms at $\lambda = 1083$ nm, especially with the advent of fiber amplifiers that generate more than 1 W of $\lambda=1083$ nm light. He atoms with an initial velocity of 1000 m/s can be brought to rest in less than 1 cm.

This research was supported by the U.S. ONR and ARO.

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