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Stimulated focusing and deflection of an atomic beam using picosecond laser pulses

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Using the stimulated force exerted by counterpropagating π pulses from a mode-locked Ti:sapphire laser we have focused a beam of laser-cooled cesium atoms along one dimension to about 57% of its original width in the detection zone. We determined the force profile outside and inside the overlap region of the pulses and found agreement with an earlier theoretical prediction. The scheme does not require an effective two-level system and is therefore suitable for a large variety of elements. [S1050-2947(97)51011-0]

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Trapping and manipulation of neutral atoms using laser light have become important tools in atomic physics. Stimulated light forces have attracted long-standing attention because they overcome the saturation limit of spontaneous light forces. The double-π-pulse technique first proposed by Kazantsev in 1974 [1] relies on the absorption of a photon from a pulsed laser beam and subsequent stimulated emission into a counterpropagating laser beam. Using high-repetition-rate, pulsed laser sources the photons are redistributed at a rate substantially higher than the spontaneous decay rate. The resulting force can exceed the saturation limit by orders of magnitude, at the same instance minimizing heating of the sample due to random walk in momentum space. The stimulated light force was first demonstrated by Voitsekhovich *et al.* [2], and Nölle *et al.* [7] achieved a gain by a factor of 3 over the spontaneous light force.

The force is peaked for π pulses; however, it is still present if the pulse area differs from π. As will be discussed below this is due to spontaneous decay and the light phase of the counterpropagating pulse. While spontaneous decay, though strongly suppressed, breaks the time symmetry and enhances absorption from one of the laser beams with respect to the counterpropagating beam, the light phase influences stimulated emission. This ensures a significant momentum transfer even when imperfect pulses are present, making this scheme very robust.

The broad spectrum of short laser pulses makes systems accessible that are subject to strong Doppler or Zeeman shifts and that do not necessarily possess a closed two-level transition. This could be of interest, for instance, for the manipulation of atoms with complex multilevel hyperfine structures by eliminating the need for multiple narrow-band lasers.

A unique feature is the spatial variation of the force. It will be shown that in the region where the counterpropagating pulses overlap a trapping potential exists, which initially increases harmonically from the center of the overlap region. The determined potential depth of more than 800 K for cesium atoms exceeds all known trap depths for neutral atoms. The restoring force profile was used to focus an atomic beam along one dimension.

In the double-π-pulse scheme an atomic beam is illuminated perpendicularly by counterpropagating trains of short pulses from a mode-locked laser that overlap in a region around the atomic beam axis (Fig. 1). The pulse intensity is adjusted to the π-pulse level, i.e., the integral of the Rabi frequency over time for one pulse is π, meaning that a single pulse coherently transfers a ground-state atom to the excited state and vice versa. A ground-state atom initially to the right of the overlap region first experiences a pulse from the right, which takes it to the excited state and imparts a momentum of $\hbar k$ to the left. Shortly afterwards the corresponding pulse from the left returns the atom to the ground state via stimulated emission, which transfers another momentum of $\hbar k$ to the left. Each pair of counterpropagating pulses thus transfers $2\hbar k$ towards the center of the overlap region; hence a force of $2\hbar k/T$ is obtained, where $1/T$ denotes the pulse repetition rate. For an atom initially to the left the situation is reversed, and the net force is directed once again towards the center of the overlap region.

A detailed treatment of the force [3] predicts that, within the region where the two pulses overlap, the atoms experience a restoring force towards the center of the overlap region, which increases linearly with distance from the center. The action of the laser pulses on the atomic beam is thus expected to be that of a cylindrical lens. The aperture of this lens is determined by the size of the overlap region, i.e., the pulse length. Since in the focusing experiment described below the atomic beam had a width of about 8 mm, we used 30-ps pulses corresponding to a pulse length of approximately 1 cm.

We have calculated the force profile in the region where the pulses do not overlap. Using the optical Bloch equations,

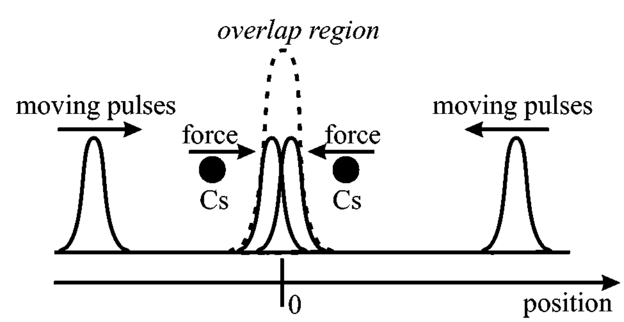

FIG. 1. Counterpropagating pulses overlapping in the vicinity of the atomic beam. Atoms at positive (negative) position experience a stimulated light force towards the left (right). In the region around zero position where the pulses partially overlap, the restoring force increases linearly with the distance to the overlap center.

Temkin [4] showed that for a train of unidirectional pulses with constant area the atomic variables approach an equilibrium state. The same can be shown for a train of counterpropagating pulses, resulting in a momentum transfer ΔP per π-pulse pair of

$$\Delta P/\hbar k = 2\,\frac{e^{-\Gamma\Delta t}-e^{-\Gamma(T-\Delta t)}}{1-e^{-\Gamma T}} \approx 2-\frac{4\,\Delta t}{T}, \qquad (1)$$

for $\Gamma T \ll 1$, where Γ denotes the spontaneous decay rate of the excited state and Δt the time delay between the pulses of a pulse pair. Note that Γ breaks the time symmetry. The temporal separation of two consecutive counterpropagating laser pulses is either Δt or $T-\Delta t$; the longer the separation the higher the probability for an atom to be in the ground state. Hence the absorption process is enhanced for one of the laser beams, which maintains the direction of the force even if non-π-pulses are present.

Our experiments were performed with a mode-locked Ti:sapphire laser (Spectra Physics Tsunami) with a pulse repetition rate of $1/T=80$ MHz tuned to the cesium D_2 transition at a wavelength of 852 nm. The pulses were characterized by an autocorrelator in the time domain and a high-finesse Fabry-Pérot interferometer (FPI) in the frequency domain. The typical pulse length of about 30 ps and the measured bandwidth of 11 GHz indicate that the sech^2 pulses were Fourier limited. Given these parameters the achievable stimulated light force is about ten times the maximum spontaneous force of $\hbar k\Gamma_{Cs}/2$ for cesium ($\Gamma_{Cs}=2\pi\times5.22$ MHz). As a frequency marker a cesium vapor cell in front of the FPI imprinted a Doppler absorption spectrum onto the mode spectrum.

In the experiment a slow cesium atomic beam with a flux of approximately 10^{10} atoms/s was produced with a pair of diode lasers using the Zeeman-slowing technique [5]. For a final longitudinal atomic velocity in the range 50–80 m/s a velocity spread of about 20 m/s was measured. After the cooling process the atomic beam had a diameter of about 8.4 mm in the interaction zone with a divergence of 0.3° for a velocity of 52 m/s.

The atomic-beam profile was velocity selectively detected downstream from the interaction zone with a charge-coupled device (CCD) camera by monitoring the fluorescence distribution induced by a diode laser beam. The angle between the laser beam and the atomic beam yielded a velocity resolution of 10 m/s.

In order to find the optimum set of experimental parameters for the focusing experiment we measured the dependence of the stimulated light force on the power of the counterpropagating pulses in an atomic-beam deflection experiment. To be able to reach pulse areas substantially higher than π, the laser beam diameter (at $1/e^2$ intensity drop) had to be reduced to $2w=1.3$ mm in the interaction zone. A curved mirror placed 330 mm from the atomic-beam axis retroreflected the laser pulses. Note that the overlap center coincides with the reflecting mirror surface. The laser light was circularly polarized and a homogeneous magnetic field of about 3 mT flux density applied parallel to the pulsed laser propagation direction defined the quantization axis for maximum coupling of the light field to the atom. Similar experiments had been done by Voitsekhovich *et al.* [6] in an amplitude modulated light field, more recently by Nölle *et al.* [7] for a thermal Na beam, and by our group for a thermal Cs beam [8].

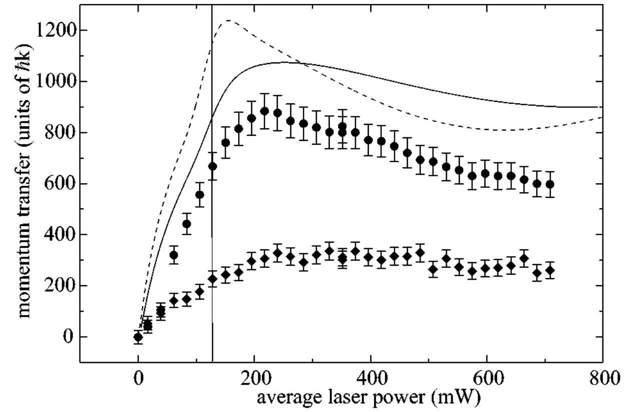

FIG. 2. Momentum transfer for the deflected part of the atomic beam vs average laser power. The spontaneous force (diamonds, return mirror blocked) saturates while the stimulated force (circles, return mirror unblocked) reaches a maximum corresponding to about three times the maximum spontaneous force. The dashed curve is a theoretical calculation; the solid curve in addition includes the vertical atomic and laser beam profiles. At 120 mW (vertical line) the π-pulse condition is met in the maximum of the Gaussian laser beam profile.

Since the cooled atomic beam was larger than the diameter of the laser beam, most of the atoms would be almost unaffected by the pulsed laser beam. Therefore the atomic beam was truncated by a 2-mm-diam circular aperture (85% transmission for the slowing lasers) immediately in front of the interaction zone. A smaller aperture could not be used because the Zeeman slowing process was disturbed due to scattering and diffraction of the slowing laser beams.

The deflection angle obtained from the CCD images of the atomic-beam profiles gives the total momentum transfer for stimulated and (with the return mirror blocked) spontaneous beam deflection (Fig. 2). The error for the momentum transfer in this and the following figures is mainly due to the uncertainty in the determination of the atomic velocity. The saturation of the spontaneous momentum transfer at about 320 $\hbar k$ is evident and corresponds to a force of $\hbar k\Gamma/2$ for an interaction length of $2w$ and an atomic velocity of 66 m/s. The stimulated force, in contrast, increases to a maximum momentum transfer of 880 $\hbar k$ and then slowly decreases.

Due to the Gaussian laser beam profile the atoms interact with varying intensities and thus varying pulse areas on their way through the interaction zone. Since the maximum momentum transfer per pulse pair occurs for pulse areas close to π, the overall deflecting force is peaked at powers where the π-pulse region has slightly moved into the wings of the laser beam profile, thus maximizing the time the atoms interact with such pulse areas. The dashed curve in Fig. 2 is a theoretical prediction based on the optical Bloch equations, taking into account the Gaussian laser beam profile along the atomic beam direction (i.e., horizontal) and transverse atomic velocities.

The effect of the light phase of the returning pulse, which depends on the distance of an individual atom to the reflecting mirror, is also included. The phase difference between

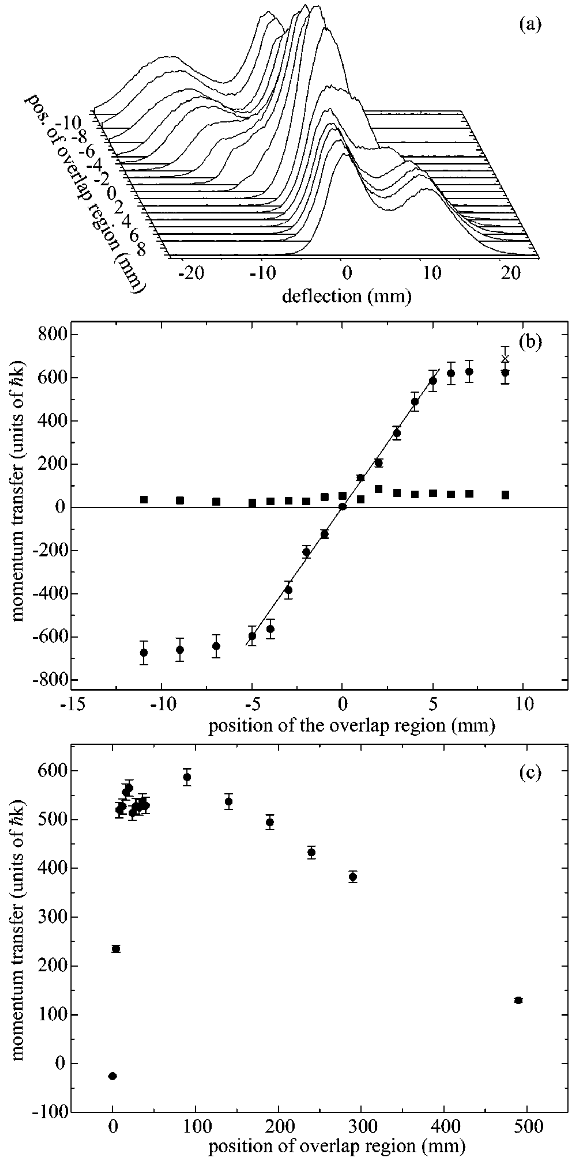

FIG. 3. Deflection of a narrow atomic beam by picosecond laser pulses: (a) atomic beam profiles for various positions of the overlap region with respect to the atomic beam; (b) momentum transfer for pulses overlapping in the vicinity of the atomic beam (circles, deflected component; squares, unaffected part of the atomic beam). Starting from negative positions of the overlap center with respect to the atomic beam only the end mirror position of the delay line was changed. This results in a slight asymmetry of the momentum transfer, which can be corrected by optimizing the overlap of the laser beams, as was confirmed (cross). (c) Momentum transfer for pulses overlapping off to one side of the atomic beam.

the rotating Bloch vector and the returning laser pulse determines the rotation axis around which the light field changes the direction of the Bloch vector. For example, for an atom initially in the ground state, applying two $\pi/2$ pulses with a phase difference of zero (π) results in a complete excitation (complete relaxation) of the atoms with an average momentum transfer of $0\hbar k$ ($1\hbar k$). Since the atomic beam width is much larger than an optical wavelength, one has to average over the light phase.

The shape of the experimental force profile and the position of maximum deflection can be reproduced much better

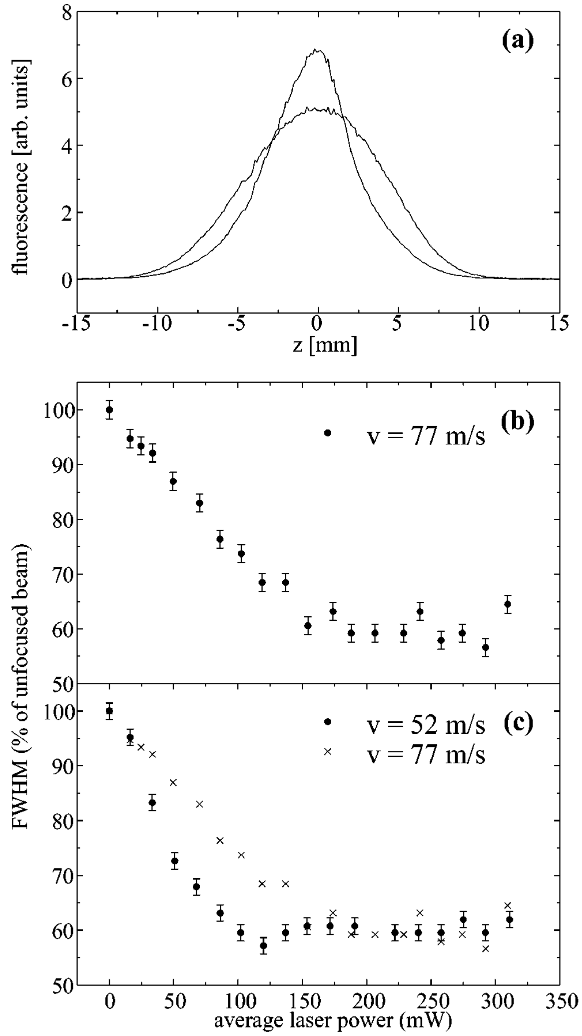

FIG. 4. Focusing of the atomic beam: (a) atomic beam profiles in the focal plane for $v = 52$ m/s; (b) and (c) normalized widths of the atomic beam in the detection zone vs average laser power for $v = 77$ m/s and 52 m/s, respectively. In (c) the data for $v = 77$ m/s are replotted (crosses) for comparison. Error bars denote the reading uncertainty.

(solid curve in Fig. 2) when the vertical atomic and laser beam profiles are also considered. The remaining difference of the experimental momentum transfer to the predicted one is attributed to the multilevel structure of the Cs atom and to inequalities in the counterpropagating laser pulse parameters like beam diameter or pulse intensities.

The predicted linear force profile within the overlap region was confirmed in a second set of experiments where the pulsed laser beam was divided into two counterpropagating beams of equal power. Using a variable delay line for one of the beams, the overlap center of the two laser pulses could be shifted left and right with respect to the atomic-beam axis. Both beams were again circularly polarized and their diameter in the interaction region was reduced to $2w = 0.8$ mm in order to reach π-pulse intensity.

Atomic-beam profiles were recorded for various positions of the overlap center [Fig. 3(a)]. The central peak in all profiles results from about 50% of the atomic beam that passed above or below the narrow interaction zone and remained fairly undeflected. A second peak appearing on the left or on the right results from stimulated deflection of the atoms. Figure 3(b) shows the transverse momentum transfer for a longitudinal velocity of 77 m/s. For small delay lengths the deflecting force increases linearly with the distance of the overlap center from the atomic-beam axis. This qualitative behavior of the force and the width of the linear part of 9.8 ± 0.2 mm around zero deflection confirms the theoretical prediction of Freegarde *et al.* [3]. For a delay of more than 10 mm the pulses no longer overlap on the atomic-beam axis and the deflection decreases according to Eq. (1) almost linearly [Fig. 3(c)]. The slope is larger than expected, since at long delays the laser geometry is modified, leading to a reduced momentum transfer. Assuming a longitudinal interaction length of $2w$, the transverse force is calculated from the measured momentum transfer. Integration of this force along the direction of the pulsed laser propagation yields a one-dimensional trapping potential with a depth of more than 800 K in the case of cesium.

The restoring linear force profile for overlapping pulses can be used to focus an atomic beam along one dimension. The focal length f for an atom moving parallel to the atomic beam axis with a longitudinal velocity v is given by $f=mv/\alpha$, where m is the atomic mass and α the slope of the linear region [Fig. 3(b)], which depends on the time an atom spends in the light field, and is hence proportional to v^{-1}. For $v=77$ m/s ($v=52$ m/s) this results in a calculated focal length of $f=187$ mm (85 mm).

To clearly demonstrate the focusing effect, we replaced the circular aperture by a slit leaving the atomic beam unobscured in the horizontal but small (2 mm) in the vertical direction. The atomic beam was detected in the vicinity of the calculated focal lengths 150 mm downstream from the interaction region. Using the results of Fig. 3(b) the overlap center was adjusted to coincide with the atomic-beam axis.

The beam profiles obtained with and without laser pulses [Fig. 4(a)] clearly show the narrowing of the beam. The normalized width of the atomic beam versus laser power is shown in Figs. 4(b) and 4(c) for longitudinal velocities $v=77$ m/s and 52 m/s, respectively. The curves reflect the power dependence of the stimulated light force (Fig. 2). The position of the focal point (infinity at zero power) approaches the detection zone with increasing laser power. For an atomic velocity of 52 m/s, the data suggest that the focal length matches the detection distance at a laser power of about 120 mW [Fig. 4(c)]. At higher power levels the stimulated force still increases, and the focal point moves between the interaction and the detection region, hence the observed beam diameter increases again. This interpretation is supported by the data for $v=77$ m/s. Here, the width still decreases in the range between 120 and 150 mW, indicating that the stimulated force still increases. However, since the focal length is proportional to v^2, it is always larger than the interaction-detection distance. For laser powers above 150 mW, the stimulated force slowly decreases. Neither a subsequent significant decrease of the width of the atomic beam for $v=52$ m/s nor an increase for $v=77$ m/s could be observed, since the reduction of the force with rising power is small (cf. Fig. 2).

The width of the atomic beam in the interaction zone is about 50% larger than the smallest beam width obtained, which clearly demonstrates the focusing properties. Since the atomic beam contains about 50% of nearly unaffected atoms, the recorded widths represent an upper limit on the width of the focused part of the atomic beam.

In conclusion, we have shown that short pulses from mode-locked lasers can be used to exert stimulated light forces on an atomic beam that deflects or focuses it. Our results for the force profile inside and outside the overlap region indicate that a neutral atom trap based on the restoring force due to counterpropagating short pulses without any further electric or magnetic fields as proposed by Freegarde *et al.* [3] should, indeed, be possible. Since the character of the broadband light force is dominated by stimulated processes, it is conceivable to extend this scheme to the mechanical manipulation of multilevel systems not accessible by narrow-band light sources.

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