Observation of a Strong Rectified Dipole Force in a Bichromatic Standing Light Wave

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We report on the observation of a strong optical dipole force which is exerted on atoms in a bichromatic standing light wave as a result of nonlinear wave-mixing processes. This force can substantially exceed the upper limit of the spontaneous light force and, in contrast to the dipole force in monochromatic standing-wave fields, acts with constant sign on a macroscopic spatial scale.

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The induced dipole force can strongly affect the motion of atoms in inhomogeneous light fields.[1,2] In standing-wave laser fields, which have been the subject of extensive studies,[3–6] a very strong dipole force can occur, greatly exceeding the principal upper limit of the spontaneous force.[1] In a single monochromatic standing wave, however, the application of this possibly strong force to manipulate the motion of atoms is restricted by the fact that the force spatially oscillates on the optical wavelength scale: Here the dipole force cannot effectively act on a macroscopic spatial scale as it vanishes in a wavelength average.

Recently, very interesting effects were considered in the works of Kazantsev and Krasnov,[7] Voitsekhovich *et al.*,[8] and Javanainen:[9] Long-wavelength dipole forces are predicted to occur in bichromatic standing-wave fields as a result of a "rectification," being due to nonlinear wave-mixing processes. Different rectification schemes were investigated for two-level atoms[7,8] and a Λ-type three-level system.[9] A relatively weak rectified dipole force may have already been observed in an experiment;[10] here, however, it at least remains unclear which rectification scheme was realized.

It is the aim of this Letter to present the first clear experimental demonstration of a strong rectified dipole force for the elementary case of two-level atoms in a bichromatic standing light wave (BSLW). Before discussing our experiment, let us explain the basic physics of the rectification effect in a simple comprehensible picture; a detailed theoretical description has already been given[7] but an illustrative explanation has not been provided up to now.

We consider the dipole force exerted on two-level atoms in a bichromatic light field under the following condition,[7] allowing for a relatively easy theoretical description. We assume that one frequency component (ω_1) of the field is strongly detuned from resonance, so that the corresponding detuning Δ_1 greatly exceeds all other relevant parameters of all points of the field:

$$|\Delta_1| \gg \Omega_1(\mathbf{r}), \Omega_0(\mathbf{r}), |\Delta_0|, \gamma ; \tag{1}$$

here $\Omega_0(\mathbf{r})$ and $\Omega_1(\mathbf{r})$ denote the space-dependent optical Rabi frequencies of the two field components, Δ_0 represents the detuning of the other field component (ω_0), and γ is the natural transition linewidth (HWHM). We furthermore neglect all effects induced by the atomic motion, like, e.g., friction forces.[4,5] This approximation is justified as long as all Doppler shifts occurring in the bichromatic field remain small compared with the natural transition linewidth.

We use a Fourier expansion of the optical Bloch equations to calculate the induced atomic dipole moment.[11] From its Fourier components oscillating with the field frequencies ω_0 and ω_1 it is straightforward to calculate[7] the two corresponding contributions $\mathbf{F}_0(\mathbf{r})$ and $\mathbf{F}_1(\mathbf{r})$ to the total dipole force $\mathbf{F}_{\rm dip}(\mathbf{r}) = \mathbf{F}_0(\mathbf{r}) + \mathbf{F}_1(\mathbf{r})$. In this way, we obtain

$$\mathbf{F}_0(\mathbf{r}) = -\tfrac{1}{2}\hbar\gamma \frac{\Delta_{\rm eff}(\mathbf{r})/\gamma}{\Delta_{\rm eff}^2(\mathbf{r})/\gamma^2 + 1 + G_0(\mathbf{r})} \nabla G_0(\mathbf{r}) , \tag{2a}$$

$$\mathbf{F}_1(\mathbf{r}) = -\tfrac{1}{2}\hbar\gamma \left[1 - \frac{G_0(\mathbf{r})}{\Delta_{\rm eff}^2(\mathbf{r})/\gamma^2 + 1 + G_0(\mathbf{r})} \right] \nabla G_1(\mathbf{r}) , \tag{2b}$$

where $G_i(\mathbf{r}) = \Omega_i^2(\mathbf{r})/2\gamma^2 = I_i(\mathbf{r})/I_{\rm sat}$ $(i=0,1)$ represent the optical saturation parameters determined by the intensities $I_0(\mathbf{r})$ and $I_1(\mathbf{r})$ of the two field components and the saturation intensity $I_{\rm sat}$ of the transition.

In Eqs. (2a) and (2b) the effective detuning parameter

$$\Delta_{\rm eff}(\mathbf{r}) = \Delta_0 + \gamma^2 G_1(\mathbf{r})/\Delta_1 \tag{3}$$

takes into account that the field (ω_0) closer to resonance sees a *light shift* of the transition frequency induced by nonlinear wave mixing with the strongly detuned field (ω_1). We note that light-shift effects of this kind are well known in laser spectroscopy;[12] also, quite recently their possible importance in laser-cooling experiments was pointed out.[13,14] In fact, in our case, the light-shift effect plays the essential role for the rectification of the dipole force in a BSLW, as will be demonstrated in the following.

We now consider a field consisting of two collinear standing waves (ω_0, ω_1) interacting with the optical two-level transition. The corresponding intensity profiles are described by $I_0 = \bar{I}_0[1 - \cos(2k_0x)]$ and $I_1 = \bar{I}_1[1 - \cos(2k_1x)]$, with $k_0 = \omega_0/c$ and $k_1 = \omega_1/c$. Because of the small wave-number difference $\delta k = k_0 - k_1$ ($|\delta k| \ll k_0, k_1$) the two sinusoidal standing-wave profiles display a spatial phase shift $\phi = 2\delta k x$ with respect to each other: ϕ oscillates in space with a period $L_0 = \pi/\delta k$ greatly exceeding the optical wavelength $\lambda = 2\pi/k \simeq 2\pi/k_0 \simeq 2\pi/k_1$ and thus can be regarded as constant over some optical wavelengths.

Figure 1 illustrates how the light-shift effect leads to the rectification of the force component $\mathbf{F}_0(x) = F_0(x)\hat{\mathbf{x}}$. In our example, we assume $\phi = 3\pi/2$, $\bar{G}_0 = \bar{I}_0/I_{\text{sat}} = 2000$, $\Delta_0 = 10\gamma$, $\bar{G}_1 = \bar{I}_1/I_{\text{sat}} = 3000$, and $\Delta_1 = -300\gamma$; these parameters fulfill the condition $\Delta_0 + \gamma^2 \bar{G}_1/\Delta_1 = 0$ for an optimum rectification, as will be discussed in detail elsewhere. According to Eq. (3), the light shift $\Delta_{\text{eff}}(x) - \Delta_0$ occurs proportional to the intensity $I_1(x)$ of the strongly detuned field. As a consequence, the effective detuning $\Delta_{\text{eff}}(x)$ displays a spatial oscillation [see Fig. 1(b)]; i.e., a spatially alternating sign reversal occurs. This leads to a corresponding spatially alternating sign reversal in the force $F_0(x)$, which is an odd function of Δ_{eff}. In our example, the sign of $F_0(x)$ in the BSLW [see the solid line in Fig. 1(c)] is reversed exactly where it would be negative in a monochromatic standing wave [see the dashed line in Fig. 1(c)]; otherwise, the force keeps its positive

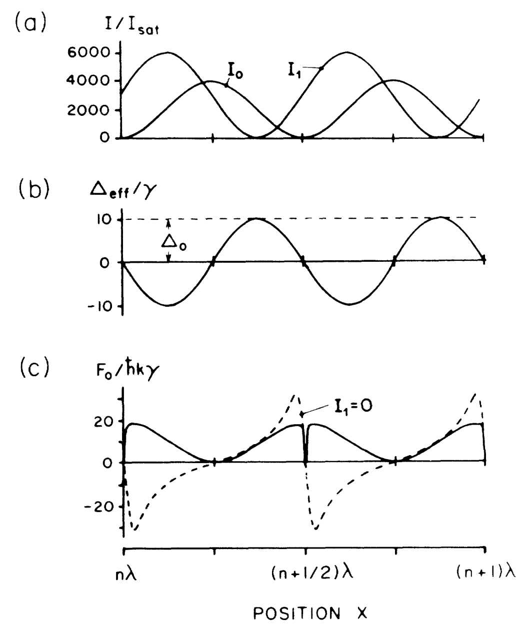

FIG. 1. Illustration of the light-shift-induced rectification of the dipole force component $F_0(x)$ in a BSLW, where $\bar{G}_0 = 2000$, $\bar{G}_1 = 3000$, $\Delta_0 = 10\gamma$, $\Delta_1 = -300\gamma$, and $\phi = 3\pi/2$ are assumed. (a) The intensity profiles $I_0(x)$ and $I_1(x)$ of the two standing-wave components. (b) Solid curve, the space-dependent effective detuning $\Delta_{\text{eff}}(x) = \Delta_0 + \gamma^2 G_1/\Delta_1$; dashed line, the initial detuning Δ_0 without the light-shift effect. (c) Solid curve, the force profile $F_0(x)$ resulting in the BSLW; dashed curve, for comparison, the corresponding force profile which would result in the absence of the second, light-shifting standing wave ($I_1 = 0$).

sign. This, obviously, means *spatial rectification* of the dipole force: An overall-positive force profile $F_0(x)$ results. The corresponding "*rectified dipole force*," defined as force $\langle F_0 \rangle$ averaged over the rapid variations on the λ scale, is of the order of the maximum dipole force in a standing wave and thus can greatly exceed the upper limit $\hbar k \gamma$ of the spontaneous force.

The second component $F_1(x)$ [see Eq. (2b)] exhibits a similar rectification effect. There the underlying mechanism is a space-dependent saturation of the optical transition leading to a periodical decrease of the force; this is mathematically described by the term in square brackets in Eq. (2b), which directly represents the population probability difference between the ground and excited states. Without going into more details here, we note that this saturation-induced rectification in $F_1(x)$ turns out to be much less effective in obtaining a strong force than the light-shift-induced rectification in $F_0(x)$.

Quite comprehensibly, the phase $\phi = 2\pi x/L_0$ plays a crucial role for the rectification effect both in force components F_0 and F_1 and in the total force F_{dip}: For $\phi = 0, \pi$ no rectification takes place, and for $\phi = \pi/2$ ($\phi = 3\pi/2$) the maximum negative (positive) rectified force occurs. Thus, theory predicts a spatial period $L_0 = \pi/\delta k \gg \lambda$ of the rectified dipole force $\langle F_{\text{dip}} \rangle$.

In our experiment, schematically shown in Fig. 2, we studied the deflection of an atomic beam perpendicularly injected into a BSLW. Our beam of sodium atoms emitted from an oven with a temperature of ~ 620 K was shaped by two diaphragms (round holes with diameter 0.25 mm) separated by 290 mm. The residual gas pressure in the vacuum chamber was 10^{-6} mbar. The interaction of the atoms with the deflecting light took place 10 mm behind the second diaphragm.

The radiation for the deflecting light field was obtained from the two-frequency laser described in Ref. 15. This laser provided a beam consisting of two collinearly

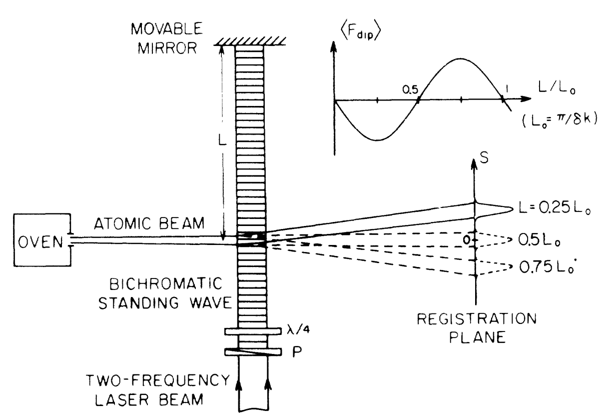

FIG. 2. Scheme of the experiment to observe the rectified dipole force in a BSLW. P, polarizer; $\lambda/4$, quarter-wave plate. Inset: Periodical dependence of the rectified dipole force $\langle F_{\text{dip}} \rangle$ on the distance L between interaction region and mirror.

propagating Gaussian TEM_{00} modes with approximately equal power $P_1 = P_2 = 25$ mW and a frequency separation $\Delta\omega/2\pi = 1.45$ GHz; according to theory, a corresponding period of $L_0 = 10.3$ cm of the rectified dipole force can be expected.

In atomic sodium, as is well known, the $F=2$-$F'=3$ transition of the hyperfine-split D_2 line excited with circularly polarized light offers a two-level system.[16] We tuned the higher-frequency mode (ω_0) of our laser close to resonance with this transition, choosing a positive detuning $\Delta_0/2\pi = +140$ MHz. This value was, on one hand, small enough for a sufficient excitation of the two-level transition. On the other hand, it turned out to be large enough to prevent a strong unwanted excitation of the $F=2$-$F'=1,2$ transitions, which leads to an optical pumping of the atoms into the $F=1$ ground state. The other field component (ω_1) was strongly detuned from the two-level transition ($\Delta_1/2\pi = -1.31$ GHz) as well as from all other transitions of the hyperfine-split line. For this choice of laser frequencies, the condition of a two-level system is realized, allowing for a clear interpretation of the experimental results in terms of the light-shift effect and not in terms of optical pumping as discussed by Javanainen.[9]

The plane mirror (see Fig. 2) was accurately aligned for exact backward reflection of the laser beam. An optical isolator prevented feedback into the laser and provided circular polarization of the light. The beam waist of the weakly focused laser beam with a diameter $d = 0.4$ mm ($1/e$ intensity drop) was located in the mirror plane. Here the mean intensity in the beam center of each of the two standing-wave fields was $\bar{I}_0 = \bar{I}_1 \simeq 40$ W/cm^2, corresponding to the saturation parameters $\bar{G}_0 = \bar{G}_1 \simeq 6000$.

The distance L between mirror and interaction region remained small compared with the confocal parameter $b = \pi d^2/2\lambda \simeq 40$ cm in all our experiments. In this case, the wave fronts are sufficiently planar so that no significant beam deflection can result from a channeling of the atoms.[17] We also very carefully aligned the perpendicularity of laser beam and atomic beam with an accuracy of ± 0.5 mrad in order to exclude a beam deflection on account of the friction force.[18]

The transverse profile of the deflected atomic beam was scanned 290 mm behind the interaction region. Here the use of a single-frequency probe laser beam, intersecting the atomic beam at an angle of 76°, allowed for a velocity-selective detection:[17] We monitored the beam profile of those atoms in the ground state ($F=2$) of the two-level transition with a longitudinal velocity of $v = 800$ m/s.

We measured the deflection profiles resulting from various positions in the BSLW; i.e., we varied the distance L between mirror and interaction region. Characteristic beam profiles, observed for the three most significant distances $L = 0.25L_0$, $0.5L_0$, and $0.75L_0$ ($\phi = \pi/2$, π, and $3\pi/2$, respectively), are shown as solid curves in Fig. 3; for comparison, the corresponding initial beam profiles observed in the absence of the BSLW are displayed as dashed curves. We are interested in the displacements of the center of mass of the beam profile since they reflect the average deflecting force. We note that the additional broadening, showing up in a similar way as for a single deflecting standing wave, occurs on account of the different atomic trajectories through the force profile, rapidly varying on the λ scale [see Fig. 1(a)], and velocity-diffusion processes.[5,6]

For $L = 0.25L_0$, the deflection profile [see Fig. 3(a)] shows a substantial displacement $S = 0.65$ mm of the beam center, which is directed towards the mirror. From this shift we estimate an average force $\langle F \rangle = -4.0\hbar k\gamma$ acting during the transit time $d/v \simeq 0.5$ μs of the atoms through the laser beam. For $L = 0.5L_0$ [see Fig. 3(b)], we registered no displacement of the beam center. For $L = 0.75L_0$ [see Fig. 3(c)], we observed a displacement $S = -0.55$ mm directed away from the mirror; here we estimate an average deflecting force $\langle F \rangle = +3.4\hbar k\gamma$ of opposite sign and nearly the same magnitude as for $L = 0.25L_0$. Our observation that the force here appears somewhat weaker is probably explained by a less ideal experimental realization of the standing-wave field for a larger distance between mirror and interaction region. As a check, we also measured the beam deflection result-

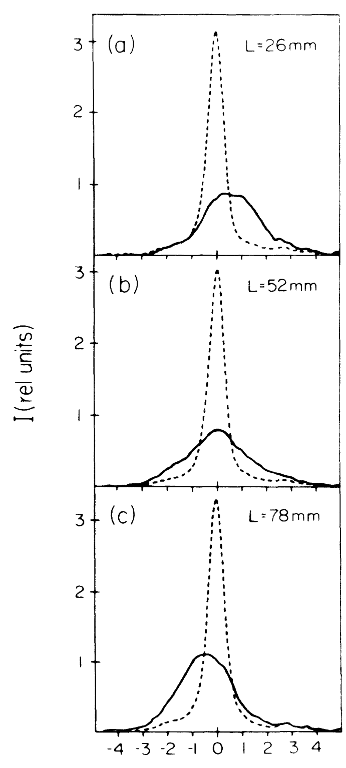

FIG. 3. Experimental atomic-beam profiles in the measured region for three different distances L (see Fig. 2). The dashed curves correspond to no-laser-field conditions.

ing from a traveling light wave, leaving all other experimental parameters unchanged. In good agreement with theoretical expectations, we observed a spontaneous force with magnitude $\sim 0.9\hbar k\gamma$.

Our atomic-beam-deflection profiles resulting from the BSLW clearly reflect an optical force with a spatial period determined by the wave-number difference of the two laser modes ($L_0 = \pi/\delta k$). This confirms that the force results from nonlinear wave-mixing processes between the two standing-wave components. Also, the strength ($\langle F\rangle > \hbar k\gamma$) and sign of the force strongly support that we, in fact, observed the *rectified dipole force* theoretically discussed above.

We note that our experimental deflection profiles cannot be expected to be fully quantitatively explained by the force described by Eqs. (2). This is mainly due to the transverse atomic velocities $v_\perp \sim \gamma/k$ occurring during the deflection process. For these velocities, exceeding our theoretical condition of weak Doppler shifts ($kv_\perp \ll \gamma$), both a friction force and a substantial decrease of the rectified force occur on account of motion-induced effects.[7] This may sufficiently explain that the rectified dipole force appeared weaker in our experiment ($\langle F\rangle \sim 4\hbar k\gamma$) than the corresponding theoretical force $\sim 10\hbar k\gamma$ calculated from Eqs. (2).

In summary, this Letter reports the first unambiguous experimental demonstration of a strong rectified dipole force exerted on two-level atoms in a bichromatic standing light wave. An explanation for the origin of this force is given in terms of a space-dependent light-shift effect. In accordance with theoretical predictions, the experimentally observed force considerably exceeds the spontaneous light force and keeps a constant sign over macroscopic distances. Thus the rectified dipole force may serve as a new tool for an effective manipulation of the motion of atoms. It may be, e.g., very useful for the design of optical traps for atoms with deep potential wells of macroscopic size.

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