Channeling of atoms in a standing spherical light wave

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One-dimensional localization of sodium atoms in a standing spherical light wave has been observed. The atoms have an oscillatory motion with an amplitude of approximately $\lambda/10$ along the nodes (or loops) of the wave.

The localization of atoms in a nonresonant light wave has been suggested.[1] In recent research, it has been inferred from observations of atomic fluorescence[2] and absorption[3] in a quasi-resonant standing light wave that atoms placed in such a wave undergo density redistribution[2] and channeling[3] under the action of the gradient force. In this Letter we report the first observation, to our knowledge, of the localization of atoms in the vicinity of the nodes (or loops) of a standing spherical light wave in the course of their being channeled along the curvilinear wave front of the laser field.

The basic idea of the experiment is schematically illustrated in Fig. 1. When atoms are being channeled along the nodes (or loops) of a light wave, the atomic trajectory must follow the wave front accurately to within $<\lambda/2$. Therefore, if the velocity of an atom entering a standing spherical light wave is tangent to the wave front, the localization of the atom must cause it to change the direction of its motion through an angle determined by the diameter of the laser beam forming the light wave and the wave-front curvature. If we assume that the atomic motion is determined mainly by the gradient force produced by the standing light wave, the angle α through which the atoms will be deflected from their initial direction of motion may be defined as

$$\alpha = 2\omega_0 z/[z_R(z^2 + z_R^2)^{1/2}], \qquad (1)$$

where ω_0 is the beam-waist radius of the Gaussian laser beam forming the standing light wave, $z_R = \pi\omega_0^2/\lambda$, and z is the distance from the beam waist to the point of intersection between the atom and the light wave.

The maximum angular divergence of the atomic beam within which the atoms still can be localized in the standing light wave is given by

$$\Delta\phi = 2(U_{\max}/E)^{1/2} = 2(2U_{\max}/M)^{1/2}/v, \qquad (2)$$

where v is the atomic velocity, M is the atomic mass, E is the kinetic energy of the atom, and $U_{\max}$ is the maximum atomic potential energy in the standing light wave, defined as

$$U_{\max} = (h\Omega/2)\ln(l_0 + p), \qquad (3)$$

where $p_0 = 8g_0^2/(\gamma^2 + \Omega^2)$ is the atomic-transition saturation parameter in the standing-wave loop and g_0 is the Rabi frequency of the traveling light wave forming the standing light wave.[4] Equation (2) also defines the angular divergence that the localized atoms will have after leaving the standing light wave.

To produce a standing spherical light wave, we used single-frequency radiation from a cw dye laser. The laser beam was focused with a lens (F = 80 mm) into the center of curvature of a spherical mirror (R = 50 mm). The beam-waist radius ω_0 in that case was 0.015 mm. The size of the standing light wave at the point of intersection with the atomic beam was 1 mm, and the radius of curvature of the wave front was 40 mm. The beam of sodium atoms was shaped by two diaphragms. The diaphragm used in the atomic source was a round hole with a diameter of d = 0.4 mm, and the other diaphragm was a slit with dimensions l_1 = 0.17 mm and l_2 = 0.5 mm. The distance between the diaphragms was L_1 = 230 mm. In that case, the angular divergence of the atomic beam was $\theta \simeq 4 \times 10^{-3}$ rad.

The distance from the slit diaphragm to the laser beam was L_2 = 10 mm, with the long side of the slit parallel to the beam. The radiation power in a single traveling wave was P_1 = 0.11 W. The atoms' angle of entry into the laser beam (Fig. 1) was $\phi = 1.25 \times 10^{-2}$

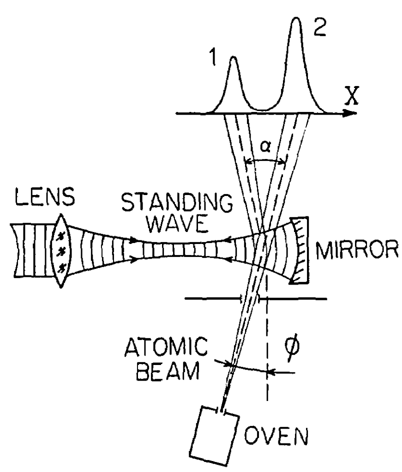

Fig. 1. Localization of atoms along the nodes (loops) of a standing light wave. 1, The atomic-beam intensity peak corresponding to localized atoms; 2, the peak corresponding to nonlocalized atoms.

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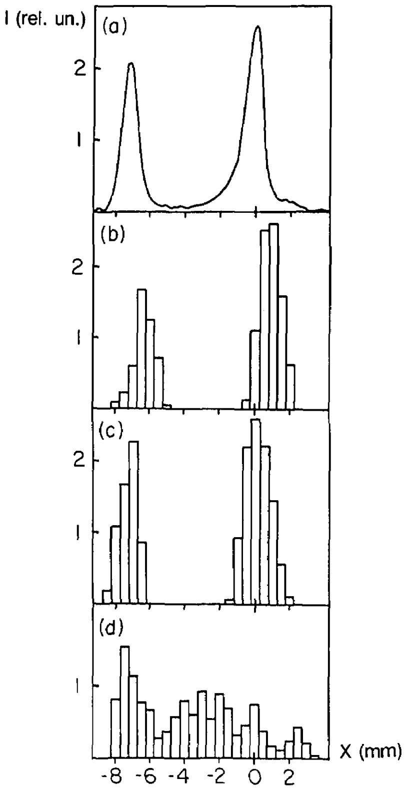

Fig. 2. Atomic-beam profile in the registration region after interaction with the standing spherical light wave: (a) experiment, (b)–(d) calculation. 1, atomic-beam intensity peak corresponding to localized atoms; 2, peak corresponding to nonlocalized atoms. The zero point on the x axis corresponds to the center of the atomic-beam profile in the absence of the laser field.

rad. The atomic-beam profile was scanned by means of a probe single-frequency radiation tuned to resonance with the $3S_{1/2}, F = 2 \rightarrow 3P_{3/2}, F' = 3$ transition. The probe beam traversed the atomic beam at an angle of 76°. The detection region was at a distance of $L_3 =$ 290 mm from the standing light wave. The probe radiation frequency was set to fall within the Doppler absorption line contour of the atomic beam, and the fluorescence of the atoms moving with a certain longitudinal velocity was detected. The velocity of the atoms subject to probing was 450 m/sec.

Figure 2(a) shows the experimental atomic-beam profile resulting from the interaction between the beam and the standing spherical light wave. The laser frequency ω_1 was detuned from the frequency of the $3S_{1/2}, F = 2 \rightarrow 3P_{3/2}, F' = 3$ transition, ω_0, by an amount of $\Omega = \omega_1 - \omega_0 = 300$ MHz. The interaction gave rise to the deflection of some atoms through an angle of α relative to their initial direction of motion and the appearance in the detection region of an additional atomic intensity peak [Fig. 2(a)]. The distance from the maximum of this peak to the center of the beam profile in the absence of the standing light wave (zero point on the x axis of Fig. 2) was 7.1 mm, which corresponded to a deflection angle of $\alpha = 2.5 \times 10^{-2}$ rad. Estimation of the atomic deflection angle by Eq. (1) yields $\alpha = 2.4 \times 10^{-2}$ rad, which agrees well with the measured value. It should be noted that so large a deflection angle was achieved because the gradient force in our experimental conditions exceeded the spontaneous light pressure force: $F_{\mathrm{grad}}^{\max}/F_{\mathrm{spont}}^{\max} \simeq 2G\gamma/\Omega \simeq 18$, where 2γ is the natural linewidth and G is the saturation parameter of the atomic transition.[4]

The measured angular divergence $\Delta\alpha$ of the atoms subjected to localization also agrees with the estimate by Eq. (2) and is 5×10^{-3} rad.

The atoms entering the standing light wave at a certain angle of $\delta\phi$ comparable with the angle $\Delta\phi$ and not along the tangent to the wave front will fail to become localized. In our experiment, this was the case with $\delta\phi = \pm 3.5 \times 10^{-3}$ rad.

Figures 2(b)–2(d) show atomic-beam profiles in the detection region after interaction with the standing light wave, calculated with allowance being made for the gradient force [Fig. 2(b)], the gradient force and friction force[5] [Fig. 2(c)], and the gradient force, friction force, and momentum diffusion[6] [Fig. 2(d)]. The displacement of the beam profile produced by the localized atoms relative to that due to nonlocalized atoms [Fig. 2(c)] was used to determine the deflection angle α, which proved to be close to both the measured value and the value found by Eq. (1). Note that failure to include the friction force in calculations causes the beam profile produced by nonlocalized atoms to be displaced from its initial position [Fig. 2(b)]. Better agreement between theory and experiment occurs when both the gradient and friction forces are taken into account [Fig. 2(c)]. Inclusion of momentum diffusion[6–8] makes the calculated beam profiles [Fig. 2(d)] wider than their experimental counterparts. This effect cannot yet be explained comprehensively.

Figure 3(a) illustrates the calculated atomic trajectories. The three trajectories correspond to three atoms entering the spherical standing light wave at the

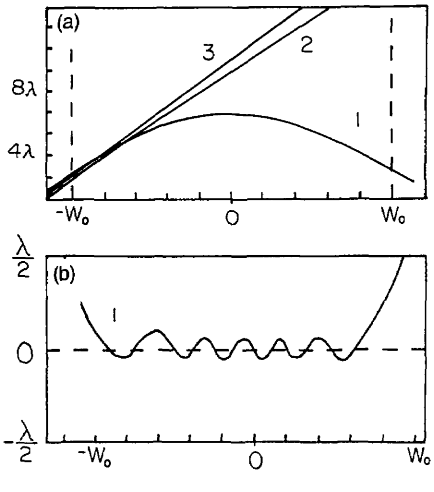

Fig. 3. Atomic trajectories in the standing light wave. (a) The character of motion of an atom as a function of the position of its point of entry into the standing light wave. Three atoms enter the wave at the same angle of $\phi = 1.2 \times 10^{-2}$ rad and at a distance of $\lambda/3$ from each other. The laser beam radius is $\omega = 0.5$ mm. Line 1, trajectory of a localized atom; lines 2 and 3, trajectories of nonlocalized atoms. (b) An enlarged scale of the trajectory of the localized atom.

same angle of $\phi = 1.2 \times 10^{-2}$ rad and at a distance of $\lambda/3$ from each other. The straight lines 2 and 3 in Fig. 3(a) correspond to the trajectories of atoms that have not been localized in the light wave and hence have not changed their direction of motion. It can also be seen from Fig. 3(a) that there are atoms that are localized in the vicinity of the nodes of the standing light wave. Such atoms oscillate with a characteristic amplitude of $\lambda/10$ [Fig. 3(b)].

Calculations show that the main factor governing the localization of an atom in a standing light wave is its point of entry into the wave.[1] At $\Omega > 0$ the localization conditions are most favorable for the atoms entering the wave near its nodes. In our experiment, we also observed the localization of atoms along the loops of the standing light wave at $\Omega < 0$.

Thus, our experimental and theoretical studies have demonstrated that changes in the trajectories of atoms are due to their localization in the vicinity of the nodes of the standing light wave. On the other hand, the results obtained show that the theory of interaction between a two-level atom and a laser field cannot quantitatively describe the movement of the sodium atom in a standing light wave.

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