Channeling Atoms in a Laser Standing Wave

C. Salomon, J. Dalibard, A. Aspect, H. Metcalf,[a] and C. Cohen-Tannoudji
Laboratoire de Spectroscopie Hertzienne de l'Ecole Normale Supérieure et Collège de France, F-75231 Paris Cedex 05, France
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We report the experimental observation of laser confinement of neutral atoms in optical-wavelength–size regions. A well-collimated atomic beam was crossed at right angles by a one-dimensional standing wave and atoms were observed to be channeled into paths between the peaks of the standing wave.

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Atomic motion in a laser standing wave is a problem which has been extensively studied because of its importance for trapping and cooling. The possibility of trapping atoms near the nodes or antinodes of an intense laser standing wave was suggested as early as 1968 by Letokhov.[1] A few years later, Kazantsev predicted the existence of velocity-dependent forces acting upon an atom moving in an intense standing wave.[2] Since then, several developments concerning the dynamics of an atom in a quasiresonant laser standing wave have been reported, including the observation of the resonant Kapitza-Dirac effect[3] and the realization of "optical molasses."[4-6]

Here we restrict our attention to the problem of trapping atoms in a standing wave. The confining force is the so-called dipole (or gradient) force which is proportional to the laser-intensity gradient and which derives from a potential $U(\mathbf{r})$ varying in space as the laser intensity. This potential $U(\mathbf{r})$ corresponds to the polarization energy of the in-phase atomic dipole moment induced by the laser electric field. There have already been some experiments on the focusing[7] and trapping[8] of atoms by dipole forces in the focal zone of traveling laser waves. However, nobody has yet demonstrated such confinement on the scale of the optical wavelength itself. A major difficulty arises from the heating of the atoms due to the fluctuations of dipole forces. This heating is proportional to the square of the field gradient and is therefore particularly important in an optical standing wave.

In this Letter, we present the experimental evidence for one-dimensional confinement of atoms by an intense laser standing wave. A well-collimated atomic beam is crossed at right angles by the standing wave which creates a periodic array of potential valleys parallel to the atomic beam. When the atomic transverse kinetic energy is low enough, atoms are observed to be channeled into these valleys.

For a two-level atom, the potential $U(\mathbf{r})$ created by the laser standing wave is given by[9]

$$U(\mathbf{r}) = \tfrac{1}{2}\hbar\delta \ln[1+2\omega_1^2(\mathbf{r})/(4\delta^2+\Gamma^2)] \quad (1)$$

and is represented in Fig. 1. Here $\delta = \omega_L - \omega_0$ is the detuning between the laser (ω_L) and the atomic (ω_0) frequencies, Γ is the natural width of the excited state, and $\omega_1(\mathbf{r})$ is the local Rabi frequency proportional to the laser electric field. Across the atomic beam, $\omega_1(\mathbf{r})$ varies as $\sin kz$, leading to a periodicity $\lambda/2$ for the potential $U(\mathbf{r})$. Along the atomic beam, $\omega_1(\mathbf{r})$ exhibits a slower variation proportional to $\exp(-r^2/w^2)$ (w is the laser-beam radius). When the atoms enter the standing wave with a low enough kinetic energy, they are guided into the channels where they oscillate in the transverse direction. The exact determination of the maximum trappable velocity is not trivial, but the intuitive criterion $mv_z^2/2 \leq \max[U(\mathbf{r})]$ appears to be valuable according to our numerical simulations. The channeling takes place near the nodes if the detuning is "blue" ($\delta > 0$) and near the antinodes if the detuning is "red" ($\delta < 0$). This discussion has actually two limitations. First, Eq. (1) is valid only in the limiting case of very low transverse velocities ($kv_z \ll \Gamma$). In fact, the force acting on the atom is also velocity dependent and, in a strong standing wave, this leads to cooling for a blue detuning and heating for a red detuning.[10-12] Second, there are fluctuations caused by the random character of spontaneous emis-

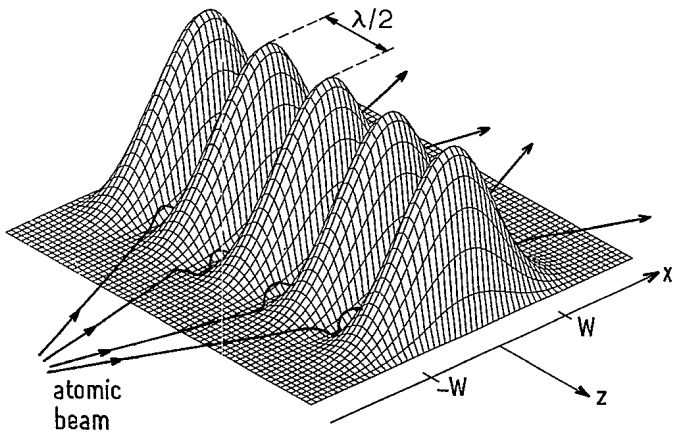

FIG. 1. Atomic potential energy $U(\mathbf{r})$ in a Gaussian standing wave aligned along 0z, for a blue detuning. Valleys correspond to nodes, and ridges correspond to antinodes.

sion.[11,12] We have found numerically that these two effects do not drastically affect the channeling because of the short transit time of the atoms through the laser beam.

To detect this channeling, we have chosen to use the atoms themselves as local probes of their own positions: Because of the spatially varying light shifts, the absorption spectrum of each atom carries information about its location in the standing wave.[13] For an atom at a node $[\omega_1(\mathbf{r})=0]$, there is no light shift and the absorption spectrum is just a Lorentzian centered at ω_0, of width Γ. Elsewhere $[\omega_1(\mathbf{r})\neq 0]$, the absorption line is shifted to[14]

$$\omega_{\text{abs}}(\mathbf{r})=\omega_0-\delta\{[1+\omega_1^2(\mathbf{r})/\delta^2]^{1/2}-1\}, \qquad (2)$$

and the maximum shift occurs at the antinodes. The absorption spectrum of the atomic beam is obtained by adding the contributions of the atoms in the various locations, weighted by the local atomic density we want to detect.

In Fig. 2, we have plotted two calculated absorption spectra. Figure 2(a) corresponds to a uniform spatial distribution of atoms (no channeling) for a blue detuning of the standing wave. It exhibits a broad structure corresponding to the range of the frequencies given by Eq. (2) for ω_1 varying from zero at a node to $\omega_1^{\max}$ at an antinode. The end peaks arise because $\omega_{\text{abs}}(\mathbf{r})$ is stationary with respect to the position z around the nodes and the antinodes (peaks N and A). Peak A is smaller than peak N because the transition matrix element is weaker near antinodes as a result of state mixing by the strong laser field.[15] Figure 2(b) is calculated with a simple periodic spatial distribution of atoms channeled near the nodes. Peak N, corresponding to atoms near the nodes, is enhanced, while peak A, corresponding to the antinodes, is weakened. By contrast, for red detuning, channeling occurs at the antinodes and will lead to an absorption spectrum with peak A enhanced and peak N weakened.

The experimental observation of channeling has been performed with the apparatus shown in Fig. 3. An effusive cesium atomic beam is formed by a multichannel array (3-mm^2 area) on a 220 °C oven (most probable velocity 300 m/s). This beam is collimated by the 2-mm diameter aperture 1 m away. The transverse velocity is then less than about 0.6 m/s (HWHM $\simeq$0.3 m/s) so that, for most atoms, $mv_z^2/2$ is not larger than the depth of the potential valleys. The atoms are prepumped into the $F=4$ hyperfine sublevel of the ground state by a 10-mW diode laser tuned to the transition $(g,F=3)\rightarrow(e,F=4)$ at 852 nm (g refers to $6S_{1/2}$ and e to $6P_{3/2}$). The intense standing wave (150 mW in each running wave, and with a beam radius of 2.3 mm) that irradiates the atomic beam at right angles is produced by a frequency-controlled cw ring dye laser (Coherent 699—Styryl 9 dye). It is tuned near the transition $(g,F=4)\rightarrow(e,F=5)$ and is σ^+ polarized along a 10-G applied magnetic field in order to approximate a two-level system. For this transition, $\Gamma/2\pi=5$ MHz and $\omega_1=\Gamma$ for a laser intensity of 2.2 mW/cm^2. The weak probe beam (0.4 mW/cm^2) is also orthogonal to the atomic beam and travels through the central part of the strong standing wave where the channeling is best. The central millimeter of this probe beam is admitted through a movable aperture to a silicon photodiode. This beam is obtained from a single-mode diode laser which is frequency stabilized by optical feedback from a confocal Fabry-Perot resonator by the technique of Dahmani, Hollberg, and Drullinger.[16] It can be scanned over 1.5 GHz while maintaining a frequency jitter less than 2 MHz. Since the fractional absorption to be detected is typically as small as 10^{-5}, we modulate the population in the $(g,F=4,m_F=4)$ level using optical pumping induced by a "chopping" diode laser. Its frequency is square-wave modulated between the transition $(g,F=4)\rightarrow(e,F=4)$ (emptying $g,F=4$) and the transition $(g,F=4)\rightarrow(e,F=5)$ (filling $g,F=m_F=4$). Synchronous detection allows us to measure the absorption of as few

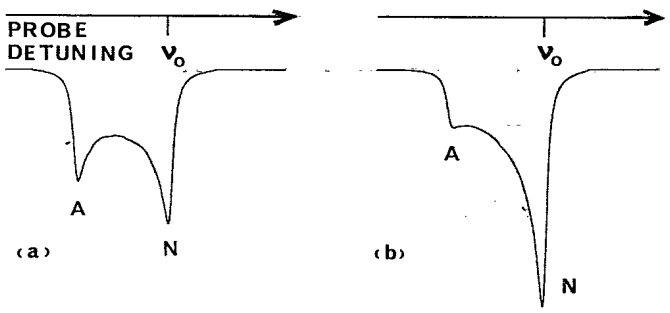

FIG. 2. Calculated absorption spectra of atoms in a strong standing wave. (a) Uniform spatial atomic distribution. Peak N at frequency ν_0 corresponds to atoms near the nodes, peak A to atoms near the antinodes. (b) Periodic triangular distribution with an atomic density at nodes five times larger than at antinodes. Channeling at the nodes enhances peak N and reduces peak A.

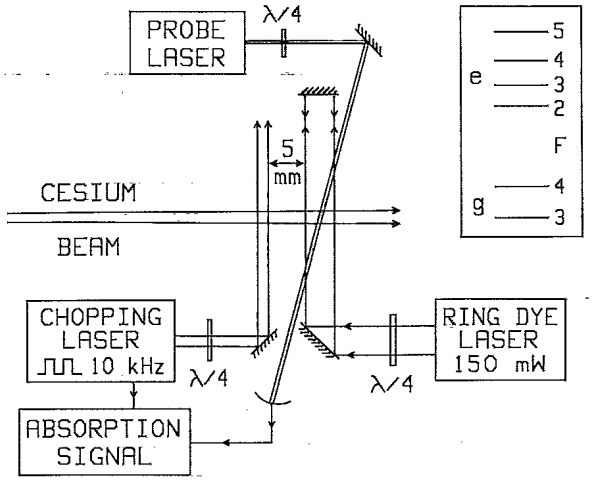

FIG. 3. Experimental setup. Inset: D_2 line of Cs.

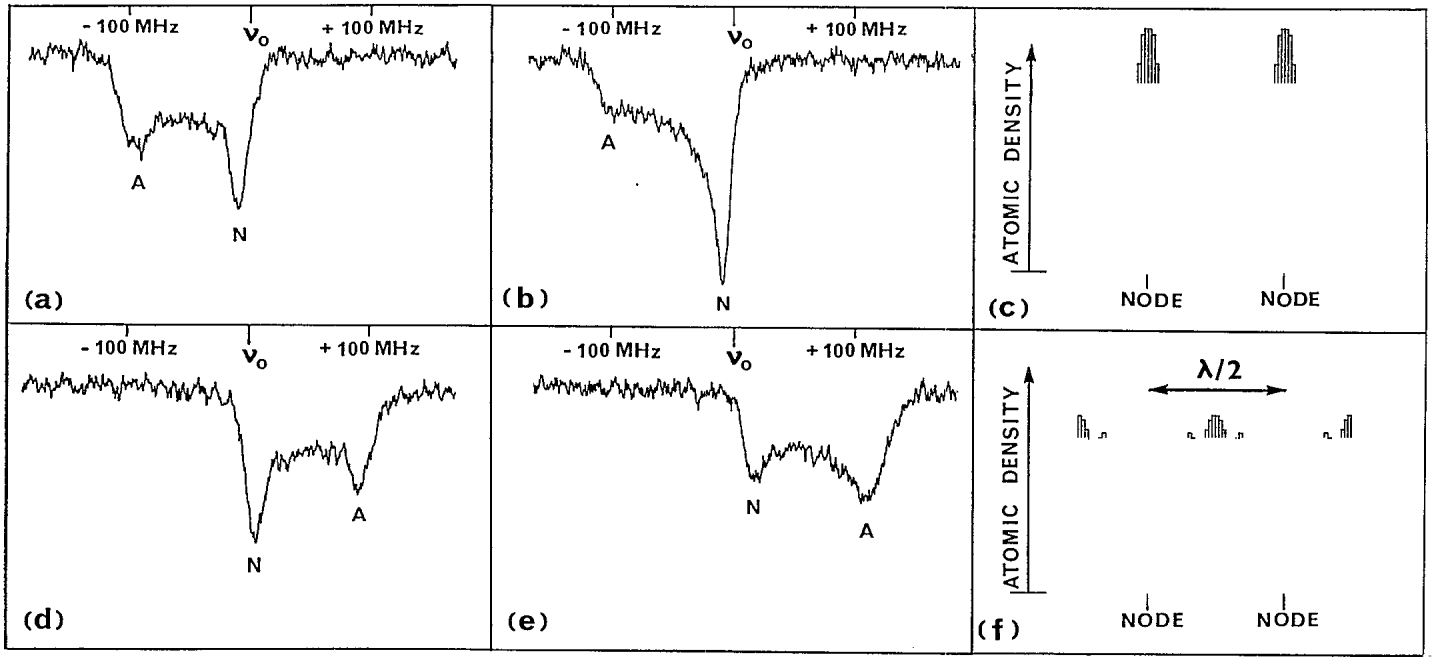

FIG. 4. Imaging atomic positions using light shifts. (a) Experimental absorption spectrum for a +150-MHz detuning, a 210-MHz Rabi frequency, and with a tilted standing wave: no channeling. (b) Same as (a) with an orthogonal standing wave: channeling near the nodes. (c) Atomic spatial distribution deduced from spectrum (b). (d)–(f) Corresponding data for a −150-MHz detuning: channeling near the antinodes.

as ten atoms in the 2-mm^3 observation volume ($S/N=1$ in 1-s integration time).

Figure 4 presents experimental evidence of of channeling, obtained for detunings $\delta/2\pi=\pm 150$ MHz, on-resonance Rabi frequency $\omega_1/2\pi=210$ MHz, and about 10000 atoms in the observation volume. This Rabi frequency is measured with the light shifts induced by the strong standing wave. The maximum height of the potential hills of Fig. 1 is then $U_0/h=45$ MHz or 2 mK, corresponding to a maximum trappable velocity ($mv_z^2/2=U_0$) equal to 0.5 m/s. For blue detuning, experimental absorption spectra are presented in Figs. 4(a) (no channeling) and 4(b) (channeling). As expected, channeling makes the peak A (antinodes) nearly disappear whereas the peak N (nodes) increases sharply. The curves with channeling were obtained by the adjustment of the orthogonality between the atomic beam and the laser standing wave to within 5×10^{-4} rad. The curves without channeling were obtained by tilting the standing wave through 5×10^{-3} rad, corresponding to an average velocity along the standing wave of 1.5 m/s. With such a velocity, channeling is no longer possible, resulting in a nearly uniform distribution of atoms across the standing wave (note that we still have $kv_z<\Gamma$).

From the experimental absorption spectra exhibiting channeling [Figs. 4(b) and 4(e)] we have deduced corresponding spatial distributions $N(z)$ of atoms in the standing wave (Figs. 4(c) and 4(f)]. These discretized $N(z)$ functions give the best least-squares fit between calculated and observed absorption spectra, which are found to coincide within the noise. Figures 4(c) and 4(f) show that we have produced gratings of atoms with a period $\lambda/2$ and with a contrast between the densities at the nodes and antinodes equal to 5 for $\delta>0$, and equal to 2 for $\delta<0$. The difference between the two contrasts, in qualitative agreement with our numerical simulations, stems from the fact that the channeled atoms are cooled for $\delta>0$ and heated for $\delta<0$.[6]

For a blue detuning, the degree of channeling would be improved by an increase of the interaction time, so that the trapped atoms could experience further cooling. Such an enhancement of channeling by cooling has been predicted theoretically.[17,18] This dissipative channeling could be observed with laser-decelerated atoms. Another attractive scheme would be to stop the atoms and then to trap them at the nodes of a three-dimensional standing wave.[1]

So far, our experiment has been interpreted in terms of classical atomic motion in the potential $U(\mathbf{r})$ associated with the mean dipole force. In order to investigate the quantum features of this motion, one can use the dressed-atom approach.[12] In this model, the atom moves in two types of periodic potentials associated with the two types of dressed states, trapping, respectively, near the nodes or near the antinodes. An interesting regime occurs when the atom makes several oscillations in a given potential before decaying by spontaneous emission to the opposite one. The quantized states of vibration of

the atom in the light field are then well resolved, and this results in sidebands on the absorption or emission lines. In our experiment, the calculated oscillation frequency is about 1 MHz, so that some improvements of our apparatus might allow this observation.

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[a]Permanent address: Department of Physics, State University of New York, Stony Brook, NY 11790.

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