Atomic Motion in a Laser 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 first suggestion to trap atoms near the nodes or near the antinodes of a non-resonant laser standing wave was made about twenty years ago by LETOKHOV [1]. A few years later, KAZANTSEV predicted the existence of velocity dependent forces acting upon atoms moving in a standing wave and he proposed to use these forces to accelerate atoms [2]. At about the same time, the idea of radiative cooling was put forward by HANSCH and SCHAWLOW for neutral atoms [3] and by WINELAND and DEHMELT for trapped particles [4]. In such a scheme, one supposes that the forces due to the two counterpropagating waves can be added independently, which means that the intensity of the standing wave cannot be too high. During the last ten years, the number of theoretical and experimental papers dealing with atomic motion in a standing wave has increased considerably and it would be impossible to review here all these works.

The purpose of this paper is to present simple physical pictures based on the dressed atom approach [5] for understanding atomic motion in a standing wave. We would like also to apply these pictures to the interpretation of new experimental results obtained recently at Ecole Normale on cooling and channeling of atoms in an intense standing wave.

1. DRESSED ATOM APPROACH [5]

We consider a two-level atom with a ground state g and an excited state e, separated by $\hbar\omega_A$. We call Γ the spontaneous radiative linewidth of e. The laser field is single mode with a standing wave structure along the Oz direction and with a frequency ω_L. We denote $\delta = \omega_L - \omega_A$ the detuning between the laser and atomic frequencies (we suppose $|\delta| \ll \omega_A$).

The uncoupled states of the atom + laser photons system can be written $|e \text{ or } g, n\rangle$. They represent the atom in e or g in presence of n laser photons. We call $\mathcal{E}(n)$ the manifold of the two unperturbed states $|g,n+1\rangle$ and $|e,n\rangle$. These two states are separated by $\hbar\delta$ and they are coupled by the interaction

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hamiltonian V_{AL} describing absorption and stimulated emission of laser photons by the atom. The corresponding matrix element can be written

$$\langle e,n|V_{AL}|g,n+1\rangle = \hbar\omega_1(z)/2 \qquad (1)$$

where $\omega_1(z) = \omega_1 \sin kz$ is a z dependent Rabi frequency.

When the coupling (1) is taken into account, the two unperturbed states of $\mathcal{E}(n)$ transform into two perturbed states $|1(n)\rangle$ and $|2(n)\rangle$. These so called dressed states are linear combinations of $|e,n\rangle$ and $|g,n+1\rangle$ and their splitting $\hbar\Omega(z)$ is equal to

$$\hbar\Omega(z) = \hbar\left[\delta^2 + \omega_1^2 \sin^2 kz\right]^{1/2}. \qquad (2)$$

The full lines of Fig. 1 represent the variations with z of the energies of the two dressed states $|1(n)\rangle$ and $|2(n)\rangle$. We take $\delta > 0$, so that the unperturbed state $|g,n+1\rangle$ is above $|e,n\rangle$.

At a node ($\omega_1(z) = 0$), the two dressed states coincide with the unperturbed ones and the splitting $\hbar\Omega$ reduces to $\hbar\delta$. At an antinode, the splitting takes its maximum value and, if $\omega_1 \gg \delta$, $|1(n)\rangle$ and $|2(n)\rangle$ are approximately equal to the symmetric and antisymmetric linear combinations of $|g,n+1\rangle$ and $|e,n\rangle$.

We introduce now spontaneous emission. Since both states $|1(n)\rangle$ and $|2(n)\rangle$ of $\mathcal{E}(n)$ contain admixtures of $|e,n\rangle$, they can decay radiatively towards the two states $|1(n-1)\rangle$ and $|2(n-1)\rangle$ of $\mathcal{E}(n-1)$ which both contain admixtures of $|g,n\rangle$. It is important to note that the corresponding radiative linewidth of $|1(n)\rangle$ and $|2(n)\rangle$ depends on z. Consider for example the dressed state $|1(n)\rangle$ for $\delta > 0$. At a node, it reduces to $|g,n+1\rangle$ which is radiatively stable, so that the natural width of $|1(n)\rangle$ is then equal to zero. At an antinode and for $\omega_1 \gg \delta$, the weight of the unstable excited state e in $|1(n)\rangle$ is ½ so that the natural

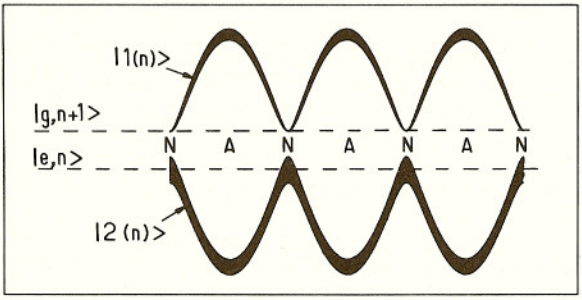

Figure 1 Spatial dependence of the dressed state energies in a standing wave (full lines). The thickness of the lines is proportional to the radiative linewidth of the levels. The dotted lines represent the unperturbed energy levels.

width of $|1(n)\rangle$ is equal to $\Gamma/2$. Similarly, the natural width of $|2(n)\rangle$ is equal to Γ at a node (since $|2(n)\rangle$ reduces then to $|e,n\rangle$) and to $\Gamma/2$ at an antinode.

2. ATOMIC ANALOGUE of the "SISYPHUS MYTH" : STIMULATED COOLING

Consider an atom moving along the direction 0z of the standing wave and being on one of the two dressed states $|1(n)\rangle$ or $|2(n)\rangle$. We suppose that its kinetic energy $mv_z^2/2$ is large compared to the height of the hills appearing on the energy curves of each dressed state (see Fig. 1). When the atom climbs a hill, its kinetic energy decreases : it is transformed into potential energy by stimulated emission processes which redistribute photons between the two counterpropagating waves.

Consider now the effect of spontaneous emission for $\delta > 0$ (blue detuning). The analysis of the previous section shows that, for each dressed state, the spontaneous emission rate is always maximum at the tops of the hills (antinodes for levels 1, nodes for levels 2). This means that the atom will leave preferentially a dressed state at the top of a hill. It follows that, during the time spent on a given dressed state, the atom sees on the average more uphill parts than downhill ones. Consequently, it is slowed down.

This new cooling mechanism is quite different from the usual one occuring for red detuning and at low intensity [6]. The mean energy loss per fluorescence photon is of the order of the height of the hills of Fig. 1. It scales as $\hbar\omega_1$ and does not saturate at high intensity : the velocity damping time of these "stimulated molasses" can therefore be much shorter than the one of usual molasses (by a factor Γ/ω_1). Experimental evidence for such a cooling mechanism has been obtained on Cesium atoms and is discussed in detail in reference [7].

3. CHANNELING of ATOMS

We suppose now that the kinetic energy of the atom along the standing wave, $mv_z^2/2$, is smaller than the height of the hills of Fig. 1 ($mv_z^2/2 \lesssim \hbar\omega_1$). This can be achieved for example by crossing at a right angle a one dimensional standing wave by a sufficiently well collimated atomic beam.

Figure 2 represents the energy surface of the dressed state $|1(n)\rangle$ which, for a blue detuning, connects to $|g,n+1\rangle$ out of the laser beam. Along the direction 0z of the standing wave, the rapid variation of $\sin^2 kz$ in (2) leads to a periodicity $\lambda/2$. Along the mean direction 0x of the atomic beam, the variations are much smoother since they are determined by the laser beam radius w_0. Because of the wings of the gaussian beam profile, the atoms which have a very small velocity spread along 0z enter the standing wave "adiabatically" and are thereby guided into

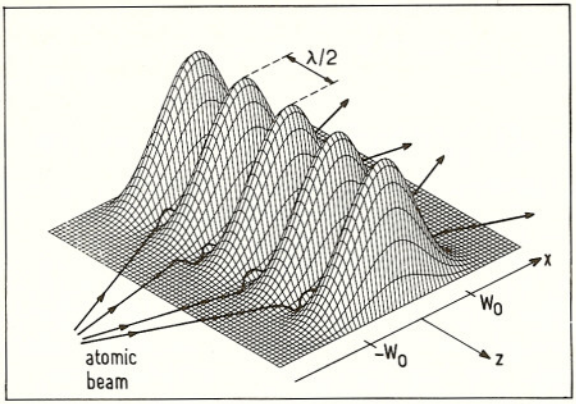

Figure 2 Energy surface of the dressed state $|1(n)\rangle$ in a gaussian standing wave propagating along Oz. Atoms with a very small transverse velocity are channelled near the nodes.

the channels where they oscillate in the transverse direction. A numerical calculation of the atomic trajectories shows that a channeling of the atoms takes place near the nodes within the standing wave. A similar calculation predicts a channeling near the antinodes for a red detuning. We have checked that spontaneous transitions between the dressed states do not drastically reduce the channeling because of the short passage 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 position. Because of the spatially varying light intensity, there are position dependent light-shifts $\Delta(z)$ which are zero at the nodes (where $\omega_1(z) = 0$) and take their maximum value Δ_M at the antinodes. The center of the atomic absorption line is therefore located between two extreme values, ω_A and $\omega_A + \Delta_M$ (for $\delta > 0$, $\Delta(z) = \delta - \Omega(z)$).

We have obtained experimental evidence for such a channeling on Cesium atoms [8]. Figure 3a gives the absorption spectrum measured on a weak probe laser beam for a uniform spatial distribution of atoms (no channeling) and for a blue detuning (Δ_M is then negative). It exhibits a broad structure corresponding to the range of frequencies between ω_A and $\omega_A + \Delta_M$. The end peaks arise because the line position is stationary with respect to the position z around the nodes (peak N) and the antinodes (peak A). The heights of these two peaks are different because the oscillator strength and the saturation factor of the atomic line depend on the intensity. The modification induced by channeling clearly appears on Fig. 3.b. Peak N, corresponding to atoms near the nodes, is enhanced while peak A, corresponding to the antinodes, is weakened. The curve with channeling (Fig. 3b) has been obtained by adjusting the orthogonality between the atomic beam and the laser standing wave to within 5.10^{-4} rad. The curve without channeling

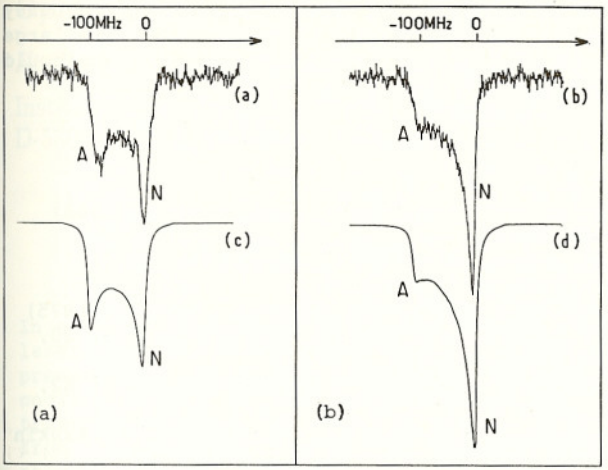

Figure 3 (a) and (b) : Experimental absorption of cesium atoms (D_2 line) at the center of a strong standing wave (Rabi frequency at the antinodes : 210 MHz ; detuning : 150 MHz ; laser beam waist : 2.3 mm), measured on a probe laser beam (power : 0,6 mW/cm² ; diameter : 1 mm). Curve (a) : no channeling. Curve (b) : channeling. (c) and (d) : calculated absorption spectra. Curve (c) : no channeling. Curve (d) : channeling.

(Fig. 3a) has been obtained by tilting the standing wave through 5.10^{-3} rad, corresponding to an average velocity along the standing wave of 1.7 m/s. With such a velocity, channeling is no longer possible.

In order to get some information on the spatial repartition of atoms N(z) in the standing wave, we have calculated absorption spectra for our experimental conditions and with simple shapes for N(z). Fig. 3c has been obtained with a uniform N(z) and is in good agreement with Fig. 3a. Fig. 3d has been calculated with a triangular shape for N(z) with a density at the nodes 5 times larger than at the antinodes. We are working on a more sophisticated deconvolution process, but the fit with the experimental curve is already of good quality. The spectra of Fig. 3 thus demonstrate the achievement of a laser confinement of neutral atoms in optical wavelength size regions.

It seems possible to improve the localization of the atoms by increasing the interaction time so that the trapped atoms could experience a further cooling for a blue detuning. Such a "dissipative channeling" has been predicted by a Monte-Carlo simulation [9] and by an analytical treatment [10]. It could be observed with laser decelerated atoms. Another attractive scheme would be to stop atoms and then to trap them at the nodes of a 3 dimensional standing wave. Finally, it would be interesting to try to observe the quantum states of vibration of the atom in

the trapping light field potential. If the oscillation frequency (which in our experimental conditions is already 1 MHz) is large compared to the natural width of the dressed state, one could observe sidebands in the absorption or emission lines.

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