Cooling Atoms with Stimulated Emission

A. Aspect, J. Dalibard, A. Heidmann, C. Salomon, 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 have observed an efficient collimation of a cesium atomic beam crossing at right angles an intense laser standing wave. This new cooling scheme is mainly based on a stimulated redistribution of photons between the two counterpropagating waves by the moving atoms. By contrast with usual radiation pressure cooling, this "stimulated molasses" works for blue detuning and does not saturate at high intensity.

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Control of atomic motion with quasiresonant laser light is a field of research which is rapidly expanding. Several experiments have demonstrated the possibility of using radiative forces for decelerating and stopping an atomic beam,[1] or for achieving a three-dimensional viscous confinement and cooling of atoms.[2] More recently, atoms have been trapped in the focal zone of a laser beam.[3]

This Letter gives experimental evidence for a new type of laser cooling, which is mainly based on stimulated emission and which can be much more efficient than the usual one involving only spontaneous emission. Let us first recall briefly the principle of usual radiative cooling[4,5] as it works in "radiation-pressure molasses." Consider at atom moving in a laser standing wave, with a light intensity weak enough (saturation parameter $s \lesssim 1$) so that the radiation pressures due to the two counterpropagating waves can be added independently. If the laser frequency ω_L is tuned below the atomic one ω_0 (detuning $\delta = \omega_L - \omega_0$ negative), because of the Doppler effect, a moving atom will get closer to resonance with the opposing wave, and farther from resonance with the copropagating wave. The radiation pressure of the opposing wave will predominate, and the atom will be slowed down. When the laser intensity is increased ($s >> 1$), this simple picture breaks down. Stimulated emission processes, responsible for a coherent redistribution of photons between the two counterpropagating waves, become predominant. They produce a heating of the atoms for a negative detuning and a cooling for a positive one. This Letter reports the first experimental observation of such a change of sign. We also emphasize the potentialities of these velocity-dependent stimulated forces which, in contrast to radiation pressure, do not saturate at high laser intensity.

Atomic motion in a strong standing wave has been theoretically studied by various authors.[6-10] Recently, a physical picture, based on the dressed-atom approach, has been proposed for the understanding of this motion.[10] It can be summarized as follows. In a strong standing wave, the energies of the dressed levels, i.e., the eigenstates of the atom plus laser-field system, oscillate periodically in space, as the Rabi frequency $\omega_1(z)$ characterizing the atom-laser coupling in z. Figure 1 represents these dressed states for a positive detuning ($\omega_L > \omega_0$). At a node $[\omega_1(z) = 0]$, the dressed states $|1,n\rangle$ and $|2,n\rangle$ respectively coincide with the unperturbed states $|g,n+1\rangle$ and $|e,n\rangle$ (an atom in the ground state g or in the excited state e, in the presence of $n+1$ or n laser photons). Out of a node $[\omega_1(z) \neq 0]$ the dressed states are linear combinations of $|g,n+1\rangle$ and $|e,n\rangle$ and their splitting $\hbar[\delta^2 + \omega_1^2(z)]^{1/2}$ is maximum at the antinodes of the standing wave. Consider now the effect of spontane-

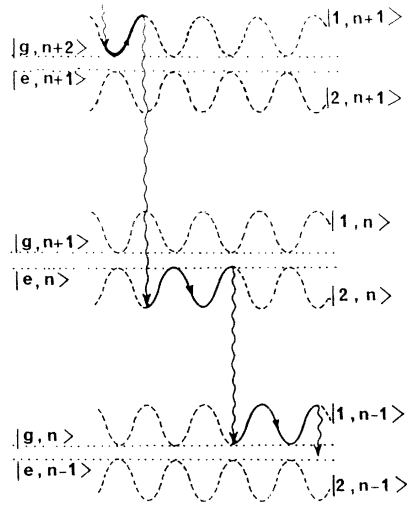

FIG. 1. Laser cooling in a strong standing wave. The dashed lines represent the spatial variations of the dressed-atom energy levels which coincide with the unperturbed levels (dotted lines) at the nodes. The solid lines represent the "trajectory" of a slowly moving atom. Because of the spatial variation of the dressed wave functions, spontaneous emission occurs preferentially at an antinode (node) for a dressed state of type 1 (2). Between two spontaneous emissions (wavy lines), the atom sees, on the average, more uphill parts than downhill ones and is therefore slowed down.

ous emission. An atom in level $|1,n\rangle$ or $|2,n\rangle$—each containing some admixture of $|e,n\rangle$—can emit a spontaneous photon and decay to level $|1,n-1\rangle$ or $|2,n-1\rangle$—each containing some admixture of $|g,n\rangle$. The key point is that the various rates for such spontaneous processes vary in space. If the atom is in level $|1,n\rangle$, its decay rate is zero at a node where $|1,n\rangle = |g,n+1\rangle$ and maximum at an antinode where the contamination of $|1,n\rangle$ by $|e,n\rangle$ is maximum. In contrast, for an atom in level $|2,n\rangle$, the decay is maximum at the nodes, where $|2,n\rangle$ is equal to $|e,n\rangle$. We can now follow the "trajectory" of a moving atom[11] starting, for example, at a node of the standing wave in level $|1,n+1\rangle$ (Fig. 1). Starting from this valley, the atom climbs uphill until it approaches the top (antinode) where its decay rate is maximum. It may jump either into level $|1,n\rangle$ (which does not change anything from a mechanical point of view[12]) or into level $|2,n\rangle$, in which case the atom is again in a valley. It has now to climb up again until it reaches a new top (node) where $|2,n\rangle$ is the most unstable, and so on. It is clear that the atomic velocity is decreased in such a process, which can be viewed as a microscopic realization of the "Sisyphus myth": Every time the atom has climbed a hill, it may be put back at the bottom of another one by spontaneous emission. We have used such a picture to derive quantitative results for the velocity dependence of the force acting upon the atom.[10] The force is found to be maximum for velocities such that the Doppler effect kv_z is on the order of the natural width Γ, or, in other words, for situations in which—as in Fig. 1—the atom travels over a distance on the order of a wavelength between two spontaneous emissions. The main point is that the magnitude of this friction force is directly related to the modulation depth of the dressed energy levels, i.e., to the Rabi frequency ω_1. As a consequence, this force increases indefinitely with the laser intensity. To conclude this theoretical part, we can analyze the energy-momentum balance in the cooling process.[10] Between two spontaneous emission processes, the total (kinetic plus potential) energy of the atom is conserved. When the atom climbs uphill, its kinetic energy is transformed into potential energy by stimulated emission processes which redistribute photons between the two counterpropagating waves at a rate ω_1. Atomic momentum is therefore transferred to laser photons. The total atomic energy is then dissipated by spontaneous emission processes which carry away part of the atomic potential energy.

This scheme has been experimentally applied to the transverse cooling of a cesium atomic beam (see Fig. 2). This beam, produced by a multichannel-array effusive source (most probable longitudinal velocity $u = 250$ m/s), is collimated to ± 8 mrad. It is irradiated at right angles (along Oz) by an intense standing wave obtained from a frequency-controlled cw ring dye laser tuned to the D_2 line at 852 nm (Styryl 9M—Coherent model No. 699-21). At the entrance of the interaction region, the intial transverse velocity spread along Oz is ± 2 m/s. The final velocity profile is analyzed by a tungsten hot-wire detector diameter (500 μm) located 2 m downstream. Such a scheme allows us to study the cooling process in the low-velocity regime (Doppler effect $kv_z \lesssim$ natural linewidth $\Gamma = 3.3 \times 10^7$ s^{-1}) where the cooling efficiency is maximum. Before entering the interaction region, all atoms are optically pumped into the $|6^2S_{1/2}, F=4\rangle$ ground-state hyperfine level by a single-mode diode laser (Hitachi HLP 1400). The cooling laser is tuned around the $|6^2S_{1/2}, F=4\rangle \rightarrow |6^2P_{3/2}, F=5\rangle$ resonance transition and σ^+ polarized. (A 10-G dc magnetic field is applied along Oz.) Because of optical pumping, the atoms are rapidly locked to the transition $|g, F=4, m_F=4\rangle \rightarrow |e, F=5, m_F=5\rangle$, which achieves

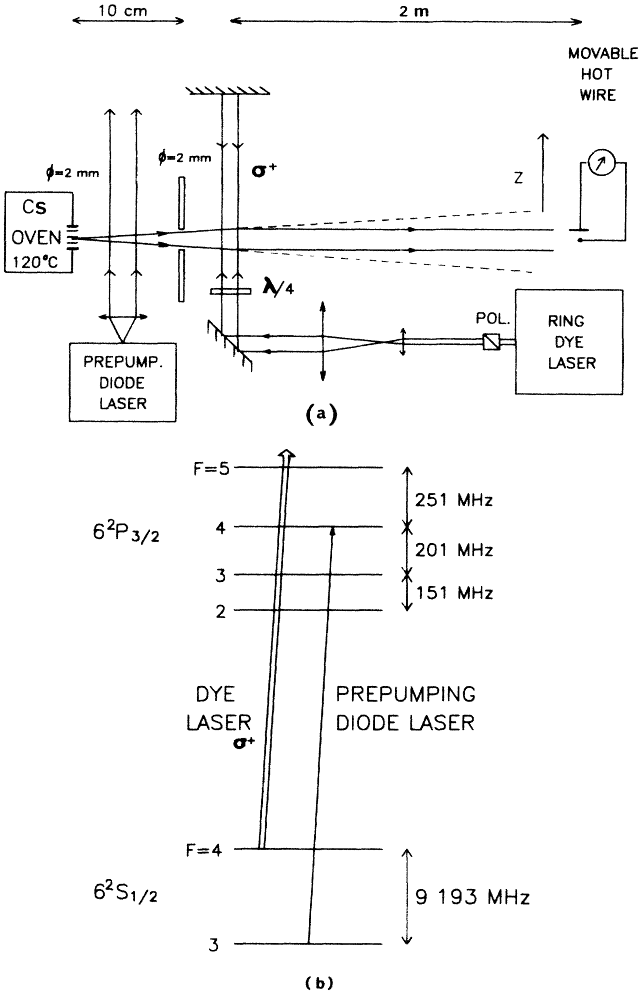

FIG. 2. (a) Experimental setup, (b) relevant cesium energy levels.

a two-level system. In the interaction region the laser standing wave has a Gaussian profile with a beam waist $w = 1.8$ mm. This leads to a transit time $2w/u$ on the order of 15 μs.

Experimental results are presented in Fig. 3. The incident laser power is 70 mW and leads to a maximum Rabi frequency of about 50 Γ. For the optimum detuning $\delta = \omega_L - \omega_0 = +6\Gamma$ (note the sign reversal compared to usual molasses), the atomic beam is strongly collimated to a narrow velocity peak of 40 cm/s half-width at half maximum (HWHM) (curve *b*). This width is 5 times narrower than that of the unperturbed atomic beam (curve *a*). For various laser powers, the peak intensity and width are found in excellent agreeemnt with a Monte Carlo calculation which simulates the sequence of events depicted in Fig. 1 for our actual experimental configuration. For the previous laser power of 70 mW but opposite detuning ($\delta = -6\Gamma$) the atomic beam is decollimated and the velocity profile exhibits a double-peak structure[13] (curve *c*). The slight asymmetry between these two peaks results from the imperfect orthogonality between the atomic beam and the laser standing wave. Note also the presence of a small additional central peak with a very narrow width of 20 cm/s. This structure, appearing consistently in the data as well as in the Monte Carlo simulation, seems to be due to a residual trapping of very low-velocity atoms at the antinodes of the standing wave.

Let us now compare our experiment with two other types of experiments dealing with deflection of atomic beams by stimulated forces.[14,15] The first one[14] describes a focusing by dipole forces for a negative detuning. This process is a *nondissipative* one, to be contrasted with the *cooling* effect reported in this Letter leading to a collimation of the atomic beam. The second one[15] deals with the diffraction of an atomic beam by a standing wave (nearly resonant Kapitza-Dirac effect). In this diffractive regime, no spontaneous emission—and consequently no dissipation—takes place. In contrast, in the experiment presented here, each atom emits about 200 spontaneous photons.[16]

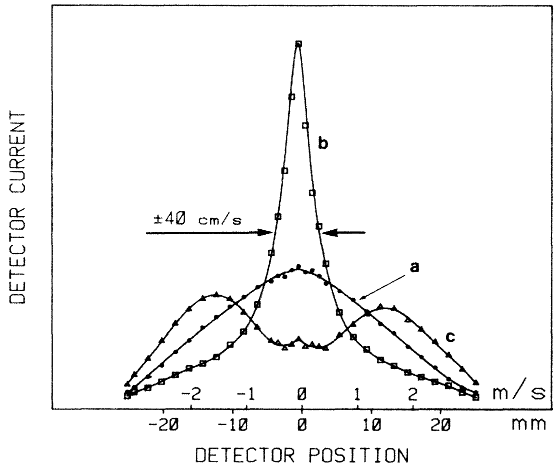

FIG. 3. Detector current vs position of the hot-wire detector. The corresponding transverse atomic velocities are given in m/s. Peak current is 2.2×10^9 atoms/s. The full lines are intended merely as visual aids. Curve *a*, laser beam off (HWHM 2 m/s); curve *b*, laser beam on with a positive detuning ($\delta/2\pi = +30$ MHz); curve *c*, laser beam on with a negative detuning ($\delta/2\pi = -30$ MHz).

We have thus achieved a new type of transverse laser cooling, operating with a positive detuning. This "stimulated molasses" appears to be very efficient: Realization of the same cooling with the usual radiation-pressure molasses would have required an interaction length one order of magnitude larger. Actually, we have checked that with our beam waist of 1.8 mm this usual molasses—obtained at the optimal detuning $\delta = -\Gamma/2$ and saturation parameter $s \simeq 1$ — has no significant effect. As a matter of fact, the minimum damping time of usual molasses is about 100 μs for Cs, while it is only 4 μs for stimulated molasses in our experimental conditions. Furthermore, since stimulated forces do not saturate, the damping time for stimulated molasses, which is inversely proportional to ω_1, could be yet more decreased by an increase in the laser power.[10] On the other hand, because of the relatively large fluctuations of dipole forces, the final velocity spread in our experiments is about 3 times larger than the limit of usual molasses. When ultimate cooling is necessary, one can use the scheme presented here for an initial rapid cooling (of special interest for fast beams) combined with usual molasses for the final stage.

Another attractive effect is suggested by our Monte Carlo calculation which predicts, for a positive detuning, a "channeling" of the atoms: On a time scale of a few hundred microseconds the atoms should concentrate at the nodes of the standing wave, with a spatial spread $\Delta z \simeq \lambda/40$ and a residual velocity spread $\Delta v_z \simeq 30$ cm/s. Such a spatially ordered structure might be observed by Bragg diffraction.

To conclude, let us emphasize the potentialities of these velocity-dependent stimulated forces in a standing wave of efficient longitudinal slowing down of aotms. The standing wave must then be swept in order to have a weak enough relative velocity with respect to the atoms, corresponding to the most efficient decelerating force.[6,10] For a cesium thermal beam, a laser intensity of 100 mW/mm^2 would produce a decelerating force one order of magnitude larger than the maximum radiation-pressure force. Consequently, the stopping distance would drop down from 1 m to about 10 cm. This might be of special interest for the realization of a compact atomic clock using slow atoms.

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[11] We suppose here that the atomic velocity is sufficiently small that we can neglect Landau-Zener transitions from one dressed level to another one. Between two spontaneous emissions, the atom then follows adiabatically a given dressed level. A possible way to take into account such Landau-Zener transitions for large atomic velocities is presented in Ref. 9.

[12] Actually, the atomic velocity slightly changes in such a process because of the recoil due to the spontaneously emitted photon. We have taken into account these recoils in our Monte Carlo simulation and found the corresponding heating negligible compared to the dipole-force heating (Refs. 8 and 10).

[13] This decollimation process does not affect all transverse velocities. Above a critical value v_0 the sign of the velocity-dependent force changes. Consequently, an atom with a small transverse velocity is accelerated until its velocity gets locked to v_0 if the interaction time is long enough. This critical velocity increases with the Rabi frequency, and is on the order of 3 m/s at the center of our interaction region. This point has been suggested to us by A. P. Kazantsev.

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[16] The results presented here differ also from the rainbow structure predicted in the deflection profiles of an atomic beam by a laser standing wave [C. Tanguy, S. Reynaud, M. Matsuoka, and C. Cohen-Tannoudji, Opt. Commun. **44**, 249 (1983)]. These profiles appear for long interaction times and when the transverse displacement of the atoms inside the laser beam is much smaller than the wavelength. They do not depend on the sign of δ.