

Dissipative atom optics

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Abstract. We present an experiment where a cloud of cold caesium atoms is dropped onto an atomic mirror formed by a laser evanescent wave, and is cooled during the reflection. This cooling is due to a single Sisyphus process, transferring atoms from one ground-state hyperfine level to another, less coupled to the evanescent wave. We compare our results with a simple one-dimensional theoretical model. We also give the first experimental evidence for a large increase in the confinement lifetime of the atoms in this 'gravitational cavity' because of the cooling process.

1. Introduction

Atomic mirrors made from a laser evanescent wave propagating at the surface of a dielectric constitute very convenient tools for atom optics and atom interferometry. The principle of this type of mirror was proposed by Cook and Hill [1] and experimentally realized by Balykin *et al.* [2]. It relies on the dipole force which tends to expel the atoms out of the high-intensity region (i.e. the region close to the dielectric). A recent review on the properties of atomic mirrors was given in [3]. In our group we demonstrated that these mirrors can provide a stable confinement of an atomic cloud for a fraction of a second [4]. Also, using time modulation of the light field, we have built atom-optics elements such as lenses [5], phase modulators [6] and interferometers [7] for the atomic waves.

Atomic mirrors, contrary to their photonic equivalent, can also provide dissipation. Using a spontaneous emission process during the reflection of the atoms, one can take advantage of the Sisyphus cooling mechanism to reduce their kinetic energy to much below the incident kinetic energy. This idea was first proposed in [8] and later investigated theoretically in detail in [9]. The atomic ground-state level has to involve at least two states which experience different and spatially dependent light shifts by the evanescent wave. A spontaneous Raman transition from the most shifted state to the other state may occur during the bouncing process, which leads to a reduction in the atomic kinetic energy.

The first experimental evidence for such a cooling process was reported in [10]. A thermal atomic beam was sent at grazing incidence onto an atomic mirror, and a non-specular reflected beam was observed, corresponding to a decrease in the atomic kinetic energy due to the Sisyphus process. Good agreement between the

experimental results and a simple theoretical model was obtained concerning the average energy loss.

We report here an experiment in which we study the elementary Sisyphus process using laser-cooled atoms dropped at normal incidence onto an evanescent wave (see also [11]). The atoms are released from a height of 3.2 mm above the mirror and they reach after the bounce an altitude in the range 0.5–1 mm. We show also that this reduction in the bouncing height translates into a significant increase in the lifetime of the trapped atoms.

2. Principle of the elementary Sisyphus process

The atomic mirror (figure 1) is formed by an evanescent light field polarized linearly and varying along the vertical direction (perpendicular to the dielectric surface) as

$$\mathbf{E}(z) = \mathcal{E}_0 \mathbf{e}_x \exp(-\kappa z), \quad (1)$$

where κ^{-1} is the decay length of the field amplitude and \mathcal{E}_0 the value of the electric-field on the interface. We restrict ourselves here to the analysis of the atomic motion along the z direction only.

The interaction of the field and the atom, which we model first as a two-level g - e system, is characterized by two parameters: the detuning $\delta = \omega_L - \omega_A$ between the laser frequency ω_L and the atomic resonance frequency ω_A for the g - e transition, and the Rabi frequency $\Omega_0 = d\mathcal{E}_0/2\hbar$, proportional to the atomic dipole moment d of the g - e transition. We assume here that the level g is stable, and that the level e has a radiative lifetime $1/\Gamma$. For a weak and off-resonance laser excitation ($\Omega^2 \ll \Gamma^2 + 4\delta^2$; $\delta \gg \Gamma$) the dipole potential coincides with the ac Stark shift of the ground state:

$$U_g(z) = \frac{\hbar\Omega_0^2}{4\delta} \exp(-2\kappa z). \quad (2)$$

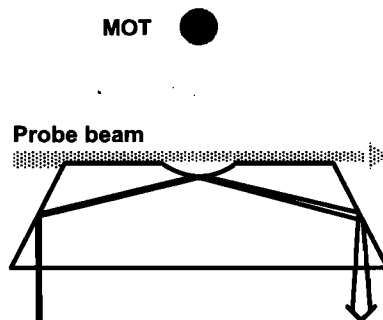


Figure 1. Atoms are dropped from a magneto-optical trap (MOT) located 3.2 mm above a mirror formed by a laser evanescent wave. They are detected through the absorption of a probe laser beam located in the vicinity of the mirror surface. This mirror surface is curved in order to stabilize the vertical paraxial motion in this gravitational cavity. The probe can detect the atoms whose apex is located higher than 400 μm above the mirror surface.

The probability for a spontaneous emission process during a time interval dt is given by

$$dn_a = \Gamma \frac{\Omega_0^2}{4\delta^2} \exp(-2\kappa z) dt. \quad (3)$$

The average number of scattered photons during a bounce is calculated by integrating equation (3) along the classical atomic trajectory which results in [4, 12]

$$n_p = \frac{\Gamma}{\delta} \frac{mv_0}{\hbar\kappa}, \quad (4)$$

where Γ is the atomic natural width, v_0 is the velocity at the entrance of the evanescent wave and m is the atomic mass.

We consider now a three-level atom, with an unstable excited state e and two stable ground states. In our experiment, these two states correspond to the hyperfine ground levels ($6s_{1/2}$, $F_g = 3$ and $F_g = 4$) of the caesium atom separated by $\Delta = 2\pi \times 9.193$ GHz. The excited state corresponds to the level $6p_{3/2}$, whose hyperfine structure can be neglected since it is small compared with the laser detunings chosen in the experiment.

The interaction between the atom and the evanescent wave gives rise to a potential which depends on the ground state (figure 2 (a)):

$$U_3(z) = \frac{\hbar\Omega_0^2}{4\delta} \exp(-2\kappa z), \quad (5)$$

$$U_4(z) = \frac{\hbar\Omega_0^2}{4(\delta + \Delta)} \exp(-2\kappa z) = \frac{\delta}{\delta + \Delta} U_3(z), \quad (6)$$

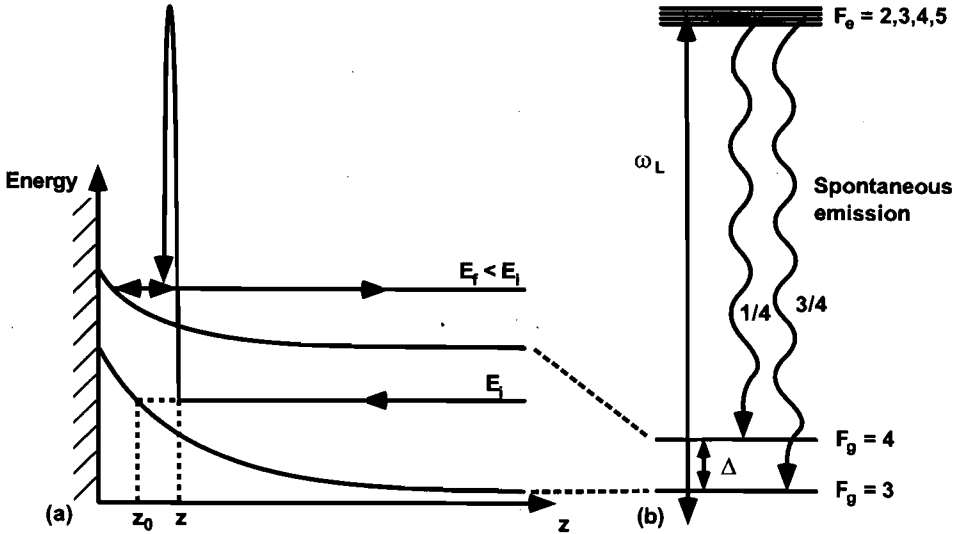


Figure 2. Sisyphus cooling in the evanescent wave. The laser detuning with respect to the state $F_g = 3$ differs by $\Delta/2\pi = 9.2$ GHz from that of $F_g = 4$. (a) The potential energy difference between the two states depends on the atom position in the evanescent wave. The atoms are initially prepared in $F_g = 3$. If a spontaneous Raman transition towards $F_g = 4$ occurs during the bounce, the atom loses potential energy and emerges from the evanescent wave mirror with a velocity reduced with respect to the incident velocity. (b) Branching ratios for the decay to the ground states.

where $\delta = \omega_L - \omega_3$ is the detuning between the laser frequency and the atomic resonance frequency corresponding to the transition $6s_{1/2}$, $F_g = 3 \leftrightarrow 6p_{3/2}$. The potential $U_4(z)$ is proportional to $U_3(z)$, but weaker.

Consider an atom in state $F_g = 3$ with kinetic energy $E_i = mv_0^2/2$ entering into the wave. It experiences the repulsive potential, so that its kinetic energy decreases, whereas its potential energy increases. If we choose the intensity and the detuning so as to get $n_p \ll 1$, the spontaneous emission process, if it occurs, will preferentially take place in the vicinity of the classical turning point z_0 , given by $E_i = U_3(z_0)$ (see figure 2). The atom may then fall back into either one of the two ground states.

If it ends up in $F_g = 3$, it will continue on its way, without being perturbed, if we neglect the atomic recoil during absorption and emission. However, the atom may also fall into $F_g = 4$. While the kinetic energy remains constant during this transition, the atom now experiences the potential $U_4(z)$ which is weaker than $U_3(z)$. After the bounce, the atomic kinetic energy $E_f = mv_f^2/2$ is thus smaller than the initial kinetic energy [8, 9].

For an atom in the state $F_g = 4$, the probability of spontaneous emission during the reflection is $n_p \delta / (\delta + \Delta)$ which is small compared with n_p as long as $\delta \ll \Delta$. We shall therefore neglect the probability that an atom in state $F_g = 4$ returns to state $F_g = 3$. The probability of a successful Sisyphus process during the bounce is then given by

$$n_s = c_{3 \rightarrow 4} n_p, \quad (7)$$

where $c_{3 \rightarrow 4}$ is the branching ratio for the excited atom to fall into the state $F_g = 4$ after spontaneous emission (figure 2(b)). For a linearly polarized laser, neglecting the small corrections due to the presence of the dielectric [13], we find that $c_{3 \rightarrow 4} = 0.25$.

The final energy E_f of an atom after the Sisyphus process occurring in z is

$$E_f = E_i \left(1 - \frac{\Delta}{\delta + \Delta} \exp[-2\kappa(z - z_0)] \right). \quad (8)$$

The loss of potential energy is maximal when the scattering process occurs at z_0 . The final energy in this case is given by

$$E_f^{\min} = E_i \frac{\delta}{\delta + \Delta}. \quad (9)$$

3. Experiment

3.1. Experimental set-up

The experimental configuration has been described in detail in [5, 6]. About 10^7 atoms are prepared in a MOT, whose centre is located 3.2 mm above the mirror. The residual vapour pressure is low (about 3×10^{-9} mbar) so that the collisions of the bouncing atoms with the residual gas are negligible. The MOT lasers are nearly resonant with the $F_g = 4 \leftrightarrow F_e = 5$ transition and have to be complemented by a repumping laser resonant with the $F_g = 3 \leftrightarrow F_e = 4$, in order to compensate for off-resonance hyperfine pumping ($F_g = 4 \rightarrow F_e = 4 \rightarrow F_g = 3$). In order to cool the atoms further, we switch to 'optical molasses' (lower intensity; larger detuning; no magnetic field). We then block the repumping laser at a time referred to as $t = 0$ in the following. Consequently almost all atoms are optically

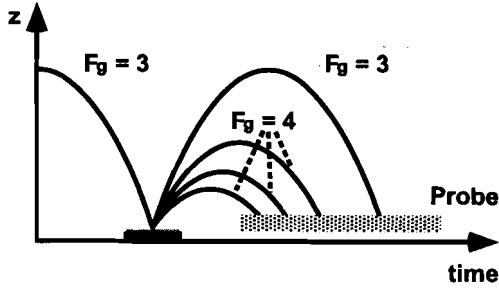


Figure 3. A fraction of ground state ($F_g = 3$) atoms bouncing on the mirror can undergo a Sisyphus transition towards $F_g = 4$ in the evanescent wave. The energy loss results in a shorter arrival time in the probe beam.

pumped into the $F_g = 3$ ground state in which they no longer interact with the light and fall under the influence of gravity. At $t = 6$ ms, we also block the main lasers resonant with the $F_g = 4 \leftrightarrow F_e = 5$ transition.

The atomic mirror is made of a fused silica prism with a concave spherical region polished into its top surface [4, 6]. The evanescent wave is generated by total internal reflection of a 100 mW diode laser beam with an angle of incidence of 58° ($\kappa^{-1} = 0.19 \mu\text{m}$). The beam waist on the mirror is about $400 \mu\text{m}$. At $t = 30$ ms the mirror laser is switched on for a period of 2 ms using an acousto-optic modulator.

The Sisyphus transition occurs during this bounce and changes the velocity of the reflected atoms. In order to analyse the energy distribution of these atoms, we perform a time-of-flight (TOF) measurement starting at $t = 43$ ms (figure 3). We record the absorption of a horizontal probe laser beam resonant with the $F_g = 4 \leftrightarrow F_e = 5$ transition. The probe is centred $450 \mu\text{m}$ above the evanescent wave mirror. It grazes the plane dielectric surface, since the mirror is situated at the bottom of the concave region $400 \mu\text{m}$ below this surface (figure 1). The probe has a horizontal width of 4 mm and a vertical width of $200 \mu\text{m}$, which limits the resolution of our TOF measurement to about 1 ms, given by the time that an atom spends in the probe. The probe may be mixed with a repumping beam $F_g = 3 \leftrightarrow F_e = 4$, so that we can choose between the detection of atoms either in $F_g = 4$ or in both hyperfine states. We can therefore determine the proportion of atoms undergoing the Sisyphus transition.

3.2. Experimental results

Figure 4(a) gives a typical atomic TOF curve. It shows the probe absorption as a function of time t . The bouncing period for atoms in state $F_g = 3$, which undergo a specular reflection, is 53 ms. These atoms cross the probe laser mixed with the repumping beam at $t = 83$ ms. Atoms undergoing a Sisyphus transition lose energy during the reflection and leave the mirror at a lower velocity and with a shorter bouncing period. They arrive first at the detection laser and they give rise to a corresponding broad peak of low height, whose maximum is located around the arrival time $t_{\text{Sis}} = 53$ ms. The signal was recorded using a mirror detuning of $\delta = 2\pi \times 3000$ MHz and a repumping laser was introduced in the probe beam so that both ground-state hyperfine levels were detected.

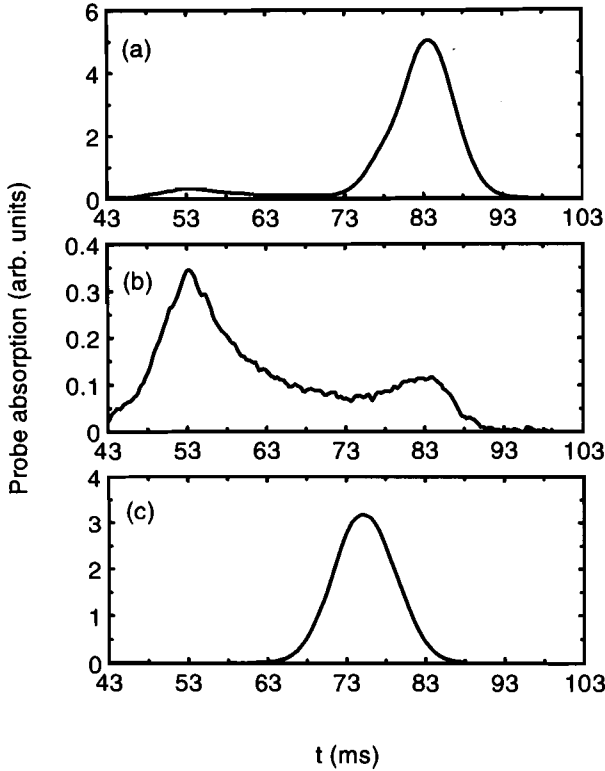


Figure 4. TOF curves: (a) atoms are released in $F_g = 3$ above a mirror detuned to $\delta/2\pi = 3$ GHz. The atoms are detected in both state $F_g = 3$ and state $F_g = 4$ using a probe beam including a repumping laser. The slowed atoms arrive first (peak centred at $t_{\text{Sis}} = 53$ ms) followed by the uncooled atoms (peak centred at $t = 83$ ms). (b) Same experiment without a repumping beam in the probe; only atoms in state $F_g = 4$ are detected. (c) Same experiment with atoms released in state $F_g = 4$. No Sisyphus effect can occur in that case since the potential for $F_g = 3$ is attractive.

In order to prove that this signal corresponds to atoms undergoing a Sisyphus process, we performed two additional experiments. First, we repeated the measurement detecting only atoms in the state $F_g = 4$, that is without a repumping laser. The result is presented in figure 4 (b). The peak previously detected at 83 ms, which corresponds to atoms in state $F_g = 3$, nearly disappears,[†] whereas the earlier observed signal is unchanged. The atoms corresponding to this broad peak maximum at t_{Sis} are thus in state $F_g = 4$. In the second experiment, atoms are dropped in state $F_g = 4$. The detuning 3000 MHz of the mirror beam is now related to the resonance $F_g = 4 \leftrightarrow F_e = 5$. As the energy difference between the two hyperfine levels is $\Delta = 2\pi \times 9193$ MHz, the mirror beam is actually red detuned with respect to the transition $F_g = 3 \leftrightarrow F_e = 2, 3, 4$. The evanescent wave potential is now attractive for atoms in state $F_g = 3$, and no Sisyphus effect

[†] We attribute the small feature which remains visible around 83 ms to atoms having bounced elastically in the evanescent wave and being transferred after the bounce to $F_g = 4$ by the stray light scattered from the prism.

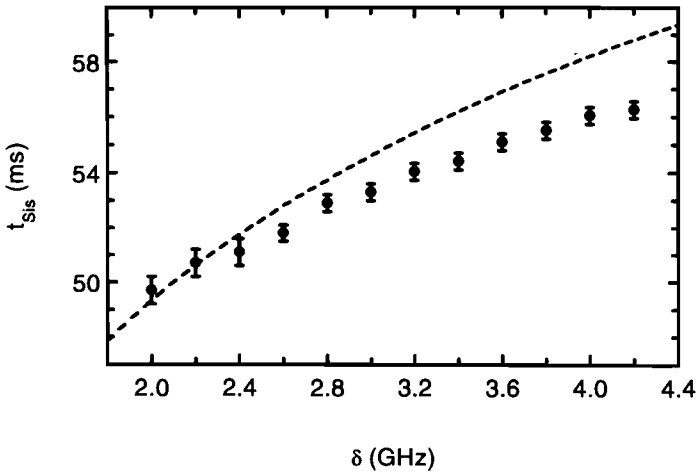


Figure 5. Peak arrival time in the probe t_{Sis} of the atoms having undergone a Sisyphus transition during the bounce: (●), experimental data; (- - -), one-dimensional prediction deduced from equation (9).

can occur. The experimental result, shown in figure 4(c), confirms this prediction since no signal is detected before the peak at 83 ms.

To gain more information on the Sisyphus process, the initial experiment is repeated for several mirror detunings $\delta/2\pi$ ranging between 2 and 4.2 GHz. The upper value is imposed by the available laser intensity. Above this value, the number of reflected atoms is too small for the signal to be analysed in a reliable way. The lower value is a consequence of the curved shape of the atomic mirror. For $\delta/2\pi < 2$ GHz, atoms which undergo a Sisyphus transition in the vicinity of the turning point z_0 lose so much kinetic energy that they can no longer escape the 400 μm concave half-sphere in the mirror. Consequently, they cannot be detected and the information about the real number of atoms in state $F_g = 4$ is lost.

We show in figure 5 the variations with δ in the time t_{Sis} , corresponding to the maximum of the signal due to the atoms having undergone a Sisyphus process during the bounce. These results are in good agreement with the simple predictions deduced from equation (9) which are plotted as a broken curve in figure 5. In [11] we showed that the agreement between these experimental results and the theoretical predictions is still improved if one takes into account the van der Waals interaction between the bouncing atoms and the dielectric substrate. In [11] we also determined from the experimental data the Sisyphus transition probability and we compared it with theoretical predictions. The agreement in this case is only qualitative, especially for large detunings where the measured Sisyphus rate exceeds the calculated rate by a factor of two.

3.3. Long confinement times in the gravitational cavity

The Sisyphus process described above leads to an important reduction in the atomic energy and a corresponding increase in the atomic de Broglie wavelength. The bouncing atoms, having been cooled, are less sensitive to defects of the atomic surface. The diffuse atomic reflection of atoms on a rough surface has been studied in detail in [14]. For a given value of the turning point z_0 , the probability of a

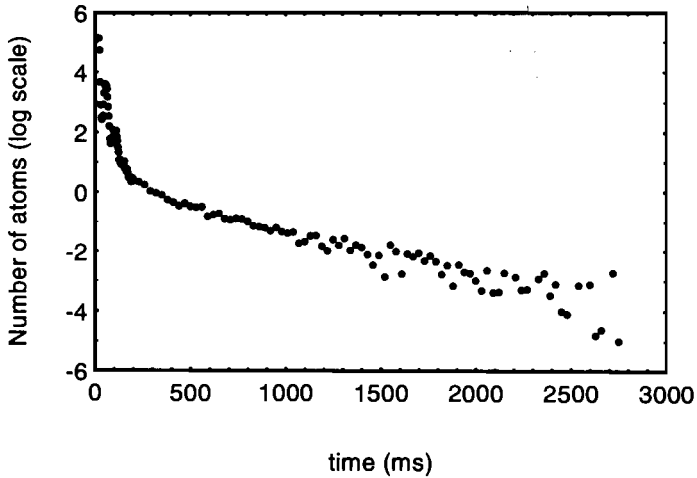


Figure 6. Number of detected atoms (logarithmic scale) as a function of the time spent in the gravitational cavity. The long-time-constant part of the curve corresponds to atoms having undergone a Sisyphus cooling process. The loss of those atoms is strongly reduced because of the decreases of firstly the heating due to spontaneous emission processes and secondly the escape rate due to surface roughness.

diffuse reflection varies linearly with the atomic kinetic energy. Since the Sisyphus cooling can reduce the atomic energy by an order of magnitude, we expect that a similar reduction should occur in the probability for a non-specular reflection of the atoms trapped in the gravitational cavity after such a cooling process. This will increase the confinement lifetime of atoms in the cavity. In addition, the detuning of the evanescent wave with respect to the relevant atomic transition after the bounce ($F_g = 4 \leftrightarrow e$) is larger than the detuning with respect to the $F_g = 3 \leftrightarrow e$ transition, which reduces the rate for spontaneous emission processes and the corresponding losses due to the heating by photon recoil.

For a drop height of about 3 mm and without any Sisyphus cooling, the typical lifetime for the atoms is between 50 and 100 ms, corresponding to a 40–60% loss per bounce [4]. This allows the observation of about ten bounces with a reasonable signal-to-noise ratio. With an experimental sequence similar to that described above, involving atoms dropped in the state $F_g = 3$ and a Sisyphus cooling process with $\delta = 0.75$ GHz, we have observed a spectacular increase of the confinement time. We have plotted in figure 6 the decrease in the number of atoms in the cavity as a function of time as measured by the fluorescence induced by the probe. The detection process is destructive so that each point in figure 6 corresponds to a new run of the experiment.

Two time constants are clearly visible in figure 6. Between 0 and 200 ms the decrease occurs with the time constant of 50 ms. This is the usual decay time of the (uncooled) atoms in the $F_g = 3$ state as they are scattered off the cavity by mirror defects and by the recoils due to spontaneous emission processes. After 200 ms the time constant for the decrease is much longer (640 ms). We have checked that the atoms contributing to this part of the signal are in the state $F_g = 4$. This is clear evidence of an increase in lifetime due to the Sisyphus cooling process. Atoms could be observed after 2.5 s, which corresponds to 120 bounces for the coldest

detectable atoms, that is the atoms whose apex is just of the order of $400\ \mu\text{m}$ (see figure 1). Note that the transverse confinement in this cavity was provided not only by the curvature of the mirror, but also using a horizontal quadrupole magnetic field ($\text{d}B/\text{d}x = -\text{d}B/\text{d}y = 15\ \text{G cm}^{-1}$) produced by four vertical wires.

4. Conclusion

We have investigated an elementary step of Sisyphus cooling using caesium atoms bouncing on a mirror formed by an evanescent wave propagating at the surface of a dielectric prism. We have shown that the loss of energy measured experimentally is in good agreement with the theoretical predictions. We have also shown that the atoms having undergone a Sisyphus process can be stored in the gravitational cavity for times much longer than uncooled atoms.

This elementary Sisyphus process is a convenient tool for accumulating a large number of atoms in a restricted domain of space, therefore increasing the quantum degeneracy of the gas. As pointed out in [8] and [10], the repetition of such processes, alternating with repumping phases transferring the atoms back to $F_g = 3$, should lead to an atomic gas with a kinetic energy of a few recoil energies $\hbar^2 k^2/2m$ only, where $\hbar k$ is the momentum of a single photon.

This Sisyphus process can also be used to populate efficiently the ground state of a potential confining the atoms in the vicinity of the dielectric prism, achieving thus a quasi-two-dimensional gas [15–17]. This could provide an efficient way to prepare a two-dimensional gas with a high quantum degeneracy.

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