Elementary Sisyphus process close to a dielectric surface

Pierre Desbiolles, Markus Arndt, Pascal Szriftgiser, and Jean Dalibard
Laboratoire Kastler Brossel, * *24 rue Lhomond, F-75231 Paris Cedex 05, France*

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We investigate both theoretically and experimentally an elementary Sisyphus process occurring during the reflection of an atom onto a laser evanescent wave propagating at the surface of a dielectric prism. Cesium atoms bouncing at normal incidence may undergo a spontaneous Raman transition between their two hyperfine levels; this leads to an efficient cooling since those levels are light shifted by a different amount by the laser-atom interaction thanks to the large hyperfine splitting. We compare the measured final energy distributions after the bounce with Monte Carlo simulations. A quantitative agreement is obtained when the van der Waals interaction between the cesium atoms and the dielectric prism is taken into account. [S1050-2947(96)00211-9]

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Since the observation of the first optical molasses [1,2], the field of laser cooling has known a tremendous development. The mechanisms at the basis of this cooling are now well elucidated. For two-level atoms, the proposed mechanism was Doppler cooling [3,4], and it was based on the radiation pressure force acting on an atom moving in a standing light wave. It was soon recognized that Doppler cooling alone could not explain the low temperatures measured in the optical molasses [5], and the concept of Sisyphus cooling was then developed [6,7]. In this description, the Zeeman substates of the atomic ground level are light shifted by different amounts; these shifts are space dependent, so that the atoms move in a series of hills and valleys. They may jump from one sublevel to another one through Raman transitions, which tend to pump the atom in the lowest sublevel. Therefore the atoms climb more than they go down in their energy diagram, which leads to cooling.

More recently, other efficient cooling schemes have also been investigated, either using lasers [8,9] or evaporation of atoms out of a trap [10–12]. Sisyphus cooling remains, however, the paradigm of an efficient cooling process, in which the spontaneous emission of a single photon may decrease considerably the energy of an atom.

Usually, in the experiments taking advantage of Sisyphus cooling, one has access to the effect of a large number of Sisyphus processes only, and the comparison between theory and experiment has to rely on an average over these many cooling cycles. On the contrary, we investigate in this paper a single Sisyphus event, occurring in the bouncing of atoms onto a mirror formed by an evanescent wave (EW) propagating at the surface of a dielectric.

The principle of this atomic mirror was proposed by Cook and Hill [13], and experimentally realized by Balykin and co-workers [14] (for a review see [15]). It relies on the so-called dipole force which tends to expel the atoms out of the high intensity region (i.e., the region close to the dielectric) provided the laser frequency is larger than the atomic resonance frequency. The application of Sisyphus cooling to those atomic mirrors was first proposed in [16], and later on investigated theoretically in detail in [17]. The atomic ground level has to involve at least two states which are shifted by a various amount by the EW; a spontaneous Raman transition from the most shifted state to the other one may occur during the bouncing process, which leads to an atomic kinetic energy after the bounce smaller than the incident one. Experimental evidence for such a cooling process was recently reported in [18]. A thermal atomic beam was sent at a grazing incidence onto an atomic mirror, and a nonspecular reflected beam was observed, corresponding to a decrease of the atomic kinetic energy due to the Sisyphus process. A good agreement between the experimental results and a simple theoretical model was obtained concerning the average energy loss.

We report here on an experiment where we study the elementary Sisyphus process using laser cooled atoms dropped at normal incidence onto an evanescent wave. In addition to the average loss of energy, we measure precisely the energy distribution of the reflected atoms using a time-of-flight (TOF) technique. We evaluate in this way the efficiency of the cooling process, as a function of the detuning of the EW. An important result of the present paper is that a quantitative analysis of the cooling process must take into account the van der Waals interaction between the atom and the dielectric prism.

The paper is organized as follows. In Sec. I we briefly describe the Sisyphus cooling of three-level atoms bouncing onto an evanescent wave and we determine the energy distribution of these atoms after the bounce. We also discuss the influence of the dielectric surface. In Sec. II we present the experimental setup and the corresponding results. Section III is devoted to an analysis of these results, in comparison with those predicted by the analytical approach of Sec. I as well as a full three-dimensional (3D) Monte Carlo analysis of the bouncing process. Finally we discuss in Sec. IV some prospects of this efficient cooling mechanism.

I. THE ELEMENTARY SISYPHUS PROCESS

A. The atomic mirror

The atomic mirror is formed by an evanescent light field propagating at the surface of a dielectric prism, resulting

*Unité de recherche de l'Ecole Normale Supérieure et de l'Université Pierre et Marie Curie, associée au CNRS.

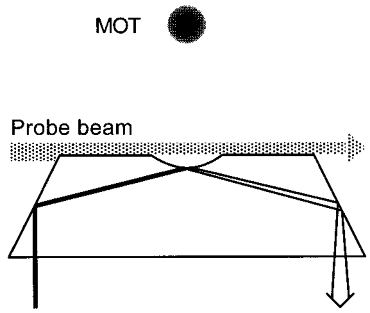

FIG. 1. Atoms are dropped from a MOT located 3.2 mm above a mirror formed by a laser evanescent wave. They are detected through the absorption of a probe laser beam located in the vicinity of the mirror surface.

from the total internal reflection of a laser running wave (Fig. 1). This wave is linearly polarized parallel to the dielectric surface; the resulting evanescent field is then linearly polarized and it varies along the vertical direction (perpendicular to the dielectric surface) as

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

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; a full 3D analysis of this motion will be given in Sec. III.

The interaction between 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 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 $1/\Gamma$. The atom-field interaction generates two classes of phenomena [19]. The reactive part of the coupling results in the dipole potential, which coincides with the ac Stark shift of the ground state g [20] for a weak laser excitation ($\Omega^2 \ll \Gamma^2 + 4\delta^2$). For $\delta \gg \Gamma$, this potential is

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

The dissipative part of the coupling leads to absorption and subsequent spontaneous emission of photons. The probability for a spontaneous process during a time interval dt is given by

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

The average number of scattered photons during a bounce is calculated by integrating Eq. (3) along the classical atomic trajectory which results in [21,22]

$$n_p = \frac{\Gamma}{\delta} \frac{m v_0}{\hbar \kappa}, \tag{4}$$

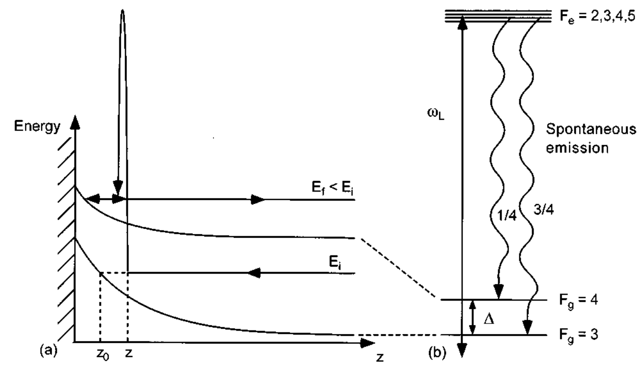

FIG. 2. Sisyphus cooling in the evanescent wave. The laser detuning with respect to the state $F_g = 3$ differs by $\Delta/2\pi = 9.2$ GHz from that of $F_g = 4$. (a) The potential-energy difference between the two states depends on the atom position in the evanescent wave. The atoms are initially prepared 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 one. (b) Branching ratios for the decay to the ground states.

where Γ, v_0, m are the atomic natural width, velocity, and mass, respectively. In the following, we restrict to situations where $n_p \ll 1$ so that n_p can be considered as the probability for a scattering event during a bounce.

B. Sisyphus effect in an evanescent field

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 cesium 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 [Fig. 2(a)]:

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

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

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

Consider an atom in state $F_g = 3$ with kinetic energy $E_i = m v_0^2/2$ 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 such 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 Fig. 2). The atom may then fall back in 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 one [16,17].

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

$$n_s=c_{3\rightarrow 4}n_p\,, \tag{7}$$

where $c_{3\rightarrow 4}$ is the branching ratio for the excited atom to fall into the state $F_g=4$ after a spontaneous emission [Fig. 2(b)]. For a linear polarization of the laser and an isolated atom, we find $c_{3\rightarrow 4}=0.25$; in Sec. III, we take into account the modifications of this coefficient due to the presence of the dielectric prism [23].

We now derive the energy distribution of the atoms after one bounce, taking into account the spatial variation of both the probability for a jump, and the energy loss in such a jump (see also [17]). The final energy E_f of an atom after a Sisyphus process occurring in z is

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

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

$$E_f^{\min}=E_i\frac{\delta}{\delta+\Delta}. \tag{9}$$

We now consider a group of N atoms in state $F_g=3$. A fraction n_sN of these incident atoms is transferred to the state $F_g=4$ at a random time during the bounce. Using (3), we derive the energy distribution $\rho(E)=dn/dE$ after the reflection:

$$\rho(E)=N\frac{n_s}{4}\frac{1}{\sqrt{E_i}}\left(\frac{\delta+\Delta}{\Delta}\right)^{1/2}\frac{1}{\sqrt{E-E_f^{\min}}}\times\left[2-\theta\left(E-E_i\frac{\delta}{\delta+\Delta}\exp(2\kappa z_0)\right)\right]. \tag{10}$$

The term involving the Heaviside function θ originates from the fraction of atoms that are transferred from $F_g=3$ to $F_g=4$ before they arrive at the turning point and whose remaining energy E_f is larger than the repulsive potential $U_4(0)$; those atoms stick to the dielectric surface and they do not contribute to the final signal.

C. Influence of the dielectric surface

As the atoms enter the EW, they also approach the dielectric surface, which creates an attractive van der Waals potential. In the case of alkali-metal ground state atoms, this interaction potential is scalar and it does not depend on the considered hyperfine level [23]:

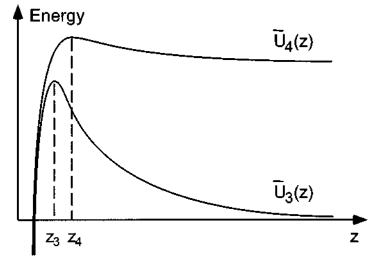

FIG. 3. Potential resulting from the combined effects of the dipole force and the van der Waals force. The exact values for z_3 and z_4 depend on the Rabi frequency, the detuning, and the transverse position with respect to the center of the Gaussian EW; a typical value is $z_{3/4}\simeq\kappa^{-1}$.

$$U_{\mathrm{vdW}}(z)=-\frac{\epsilon}{(\kappa z)^3}, \tag{11}$$

where $\epsilon=h\times 110$ kHz for Cs. The total resulting potentials $\bar{U}_{3/4}=U_{3/4}+U_{\mathrm{vdW}}$ are quite different from the initial ones (Fig. 3). They remain repulsive in a few wavelengths distance from the surface, but become attractive close to it.

The two potentials $\bar{U}_3$ and $\bar{U}_4$ reach their maximum value away from the dielectric surface in z_3 and z_4 $(z_4>z_3)$. The modified classical turning point $\bar{z}_0$ is now determined from

$$E_i=\frac{\hbar\Omega_0^2}{4\delta}\exp(-2\kappa\bar{z}_0)-\frac{\epsilon}{(\kappa\bar{z}_0)^3}. \tag{12}$$

If the turning point is far enough from the dielectric surface (more precisely if $\bar{z}_0>z_4$), the minimal achievable energy $E_f^{\min}$ of the atoms after a Sisyphus process is given by

$$E_f^{\min}=E_i\frac{\delta}{\delta+\Delta}-\frac{\Delta}{\delta+\Delta}\frac{\epsilon}{(\kappa\bar{z}_0)^3}. \tag{13}$$

On the contrary, if $z_3<\bar{z}_0<z_4$, the minimum final energy is simply the height of the potential barrier $\bar{U}_4(z_4)$. In this case, the probability for sticking after a Sisyphus process is increased since the atoms undergoing a transition in the vicinity of the turning point $\bar{z}_0$ experience an attractive potential incoming on state $F_g=4$.

In addition, the van der Waals interaction affects the probability for a Sisyphus process. First, the potential $\bar{U}_3(z)$ is smoother than $U_3(z)$. Therefore the atoms spend more time around the turning point, where the probability for a Sisyphus process reaches its maximum. Secondly, the spontaneous emission rate of an atom close to a dielectric surface is enhanced [23]; this effect is significant for $z<\lambda/2\pi$, where λ is the optical wavelength related to the atomic transition. These additional effects are included in the Monte Carlo analysis which is presented in Sec. III.

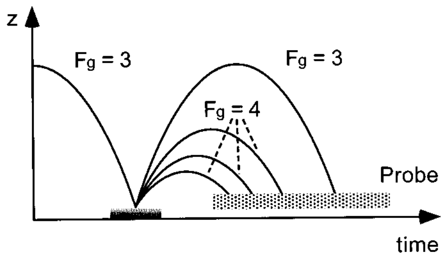

FIG. 4. A fraction of ground state ($F_g=3$) atoms bouncing on the mirror can undergo a Sisyphus transition towards $F_g=4$ in the evanescent wave. The energy loss results in a shorter arrival time in the probe beam.

II. EXPERIMENT

A. Experimental setup

The experimental configuration has been described in detail in [24,25]. Atoms are prepared in a double magneto-optical trap (MOT) configuration. In the upper cell, an ensemble of $\sim 10^8$ cold cesium atoms is loaded from the background vapor in 1 s. The atoms are then released and fall into the lower cell where they are retrapped in a second MOT, whose center is located 3.2 mm above the mirror. The residual vapor pressure in the lower cell 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 $F_g=4\rightarrow F_e=5$ transition and have to be complemented by a repumping laser resonant with the $F_g=3\rightarrow F_e=4$, in order to compensate for off-resonant hyperfine pumping ($F_g=4\rightarrow F_e=4\rightarrow F_g=3$). In order to further cool the atoms we switch to an ''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 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 $F_g=4\rightarrow F_e=5$ transition. The small remaining fraction of atoms in $F_g=4$ can be neglected in the following; indeed the detuning of the evanescent wave mirror with respect to this state is too large for the potential $\overline{U}_4$ to reflect atoms that are dropped onto the mirror from a height of 3.2 mm.

The atomic mirror is made of a fused silica prism with a concave spherical region polished into its top surface [22,24]. The EW is generated by total internal reflection of a 100 mW diode laser beam with an angle of incidence of 58° ($\kappa^{-1}=0.19$ μm). The beam waist on the mirror is about 400 μm. 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 analyze the energy distribution of these atoms, we perform a TOF measurement starting at $t=43$ ms (Fig. 4). We record the absorption of a horizontal probe laser beam resonant with the $F_g=4\rightarrow F_e=5$ transition. The probe is centered 450 μm above the evanescent wave mirror. It grazes the plane dielectric surface, since the mirror is situated at the bottom of the concave region 400 μm below this surface (Fig. 1). The probe has a horizontal width of 4 mm and a vertical width of 200 μm, which limits the resolution of our TOF measurement to ~ 1 ms, given by the time an atom spends in the probe. The probe intensity is about 0.2 mW/cm^2; at this low intensity, the number of scattered photons per atom is proportional to the time spent by this atom in the probe. In addition the optical thickness is negligible so that finally the absorption signal is proportional to the atomic density. The probe may be mixed with a repumping beam $F_g=3\rightarrow F_e=4$, 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.

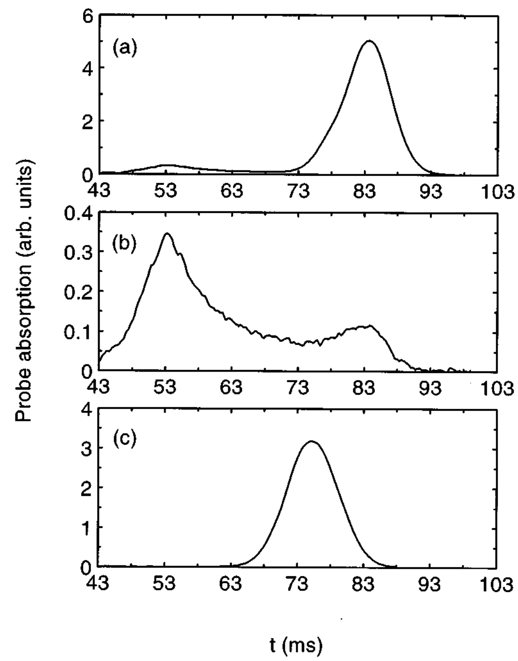

FIG. 5. Time-of-flight curves: (a) atoms are released in $F_g=3$ above a mirror detuned to $\delta/2\pi=3$ GHz. The atoms are detected both in state $F_g=3$ and $F_g=4$ using a probe beam including a repumping laser. The slowed atoms arrive first (peak centered at $t_{\mathrm{Sis}}=53$ ms) followed by the uncooled atoms (peak centered 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.

B. Experimental results

Figure 5(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 smaller 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 $t_{\mathrm{Sis}}=53$ ms. The signal was recorded using a mirror detuning of $\delta=2\pi\times3000$ MHz and a repumping laser was introduced in the probe beam so that both ground hyperfine levels were detected.

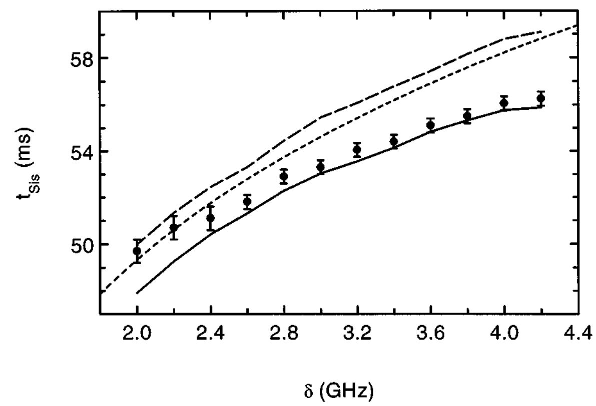

FIG. 6. Peak arrival time in the probe t_{Sis} of the atoms having undergone a Sisyphus transition during the bounce. ●, experimental data; dotted line, 1D prediction deduced from (9); continuous line, 3D Monte Carlo result including the van der Waals interaction between the atom and the dielectric prism; broken line, 3D Monte Carlo result neglecting the van der Waals interaction.

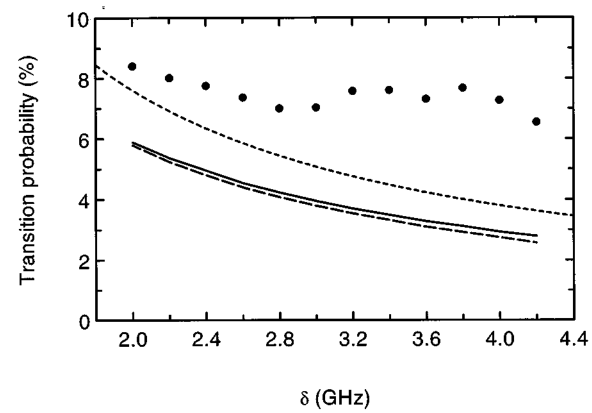

FIG. 7. Transition probability $F_g = 3 \rightarrow F_g = 4$ during the bounce on the mirror. ●, experimental data; dotted line, 1D prediction deduced from (7); continuous line, 3D Monte Carlo result including the van der Waals interaction between the atom and the dielectric prism; broken line, 3D Monte Carlo result neglecting the van der Waals interaction.

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 $F_g = 4$, i.e., without repumping laser. The result is presented in Fig. 5(b). The peak previously detected at 83 ms, which corresponds to atoms in state $F_g = 3$, nearly disappears [26], 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 $F_g = 4 \rightarrow F_e = 5$. 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 $F_g = 3 \rightarrow F_e = 2,3,4$. The evanescent wave potential is now attractive for atoms in state $F_g = 3$, and no Sisyphus effect can occur. The experimental result, shown in Fig. 5(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 GHz 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 analyzed 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 first determine the variations with δ of the time t_{Sis}, corresponding to the maximum of the signal due to the atoms having undergone a Sisyphus process during the bounce (Fig. 6). In addition we have plotted in Fig. 6 the analytical predictions derived from (9). We also use the time-of-flight signals obtained for various values of δ to evaluate the fraction of atoms which undergo a Sisyphus transition. We first determine, for a given arrival time t, the velocity of the corresponding atoms as they crossed the probe beam. We then deduce the number of atoms in this velocity class by dividing the time-of-flight signal at t by the time spent by those atoms in the probe beam. Finally we integrate the result over the arrival time t. We apply this method both for the case of a measurement without repumping laser (detection of $F_g = 4$ atoms only) and for the case where the repumping laser has been mixed to the probe (detection of all reflected atoms, independently of their hyperfine level). Figure 7 shows the results as a function of the mirror detuning. We indicate also the variations in $1/\delta$ of this fraction of atoms, expected according to the simple relation (4).

For the two quantities measured experimentally, i.e., minimal arrival time t_{Sis} and fraction of atoms undergoing a Sisyphus process, the agreement with the simple analytical model is only qualitatively correct. Significant deviations appear, especially for large detunings. Therefore we now turn to a more complete theoretical description of the Sisyphus process, which is based on a 3D numerical analysis of the atomic motion.

III. MONTE CARLO SIMULATION

While the analytical description presented in Sec. II is very convenient for deriving scaling laws for the cooling process, we do not obtain from this 1D analysis a quantitative agreement with the experimental results. The initial atomic spread in position and velocity in the MOT, as well as the temporal width of the mirror pulse, introduce a convolution of the signal. The van der Waals interaction also affects this distribution, in particular by changing the value of the minimal achievable energy. The purpose of this section is to present a Monte Carlo simulation in which all those effects can be fully taken into account.

A. Principle of the simulation

The atomic source is a cloud of atoms whose motion is treated classically. The parameters of the source are adjusted to fit the TOF peak at 83 ms, corresponding to atoms bouncing elastically on the mirror. Positions and velocities are chosen randomly according to isotropic Gaussian distributions, with standard deviations, respectively, equal to 550 μm and 2 cm s^{-1}. The evanescent wave mirror is located 3.2 mm below the center of the atomic cloud. Its transverse intensity is supposed to have a Gaussian profile. The corresponding waist $w=400$ μm is measured experimentally. The Rabi frequency entering in $\overline{U}_{3/4}$ is determined through the measurement of the maximal detuning $\delta_{\max}$ at which atoms can bounce when they are dropped from a height of 3.2 mm. For our experimental situation, we find $\delta_{\max}=2\pi\times6500$ MHz. Taking into account the effect of the van der Waals interaction, this corresponds to $\Omega_0=2\pi\times840$ MHz [27].

Atoms are released in the time interval 0–6 ms. Only atoms hitting the mirror during the 2 ms EW pulse centered at 31 ms are taken into account. For those atoms, we integrate the classical equation of motion in the potential $\overline{U}_3(z)$ using a Runge-Kutta algorithm with adaptive step size. The probability dn that a spontaneous process occurs during a time step dt is calculated, and compared to a random number r equally distributed between 0 and 1. If $dn>r$, a spontaneous emission occurs. The final state, $F_g=3$ or $F_g=4$, is determined using another random number. The evanescent wave potential is changed if the final state is $F_g=4$, and the integration continues. This method outputs the atomic state and the velocity v_s after a successful bounce. The classical trajectories during the free flight and the passing through the probe are then calculated. This simulation can be repeated for different detunings, and provides curves very similar to the experimental time-of-flight signals presented in the preceding section.

B. Results of the simulation

We now compare the results of the Monte Carlo simulation with the experimental signals obtained in the range of detuning $2\,\mathrm{GHz}\leqslant\delta/2\pi\leqslant4.2$ GHz. We have plotted in Fig. 6 the time at which the calculated time-of-flight signal for $F_g=4$ atoms is maximal, to compare it with the measured t_{Sis}. The agreement between the two quantities is quite good, except for the small values for the detuning. Two explanations for this discrepancy can be proposed. First we note that the hyperfine splitting of the excited state ($\simeq500$ MHz) is not negligible compared with δ. Secondly, the EW potential is quite large for such small detunings and an important fraction of the atoms have a turning point $\overline{z}_0$ located in a distance larger than $\lambda/2\pi$ from the dielectric; in this region, the van der Waals potential is reduced with respect to the $1/z^3$ law (11). We have also shown in Fig. 6 the prediction of a Monte Carlo simulation which does not include the van der Waals interaction. It presents significant deviations from the experimental results: the peak related to atoms in $F_g=4$ is shifted and appears later, since the minimal achievable energy $E_f^{\min}$ is higher. This discrepancy is important mostly for large detunings, for which a large fraction of the atoms approach the dielectric surface closely.

We have plotted in Fig. 7 the Monte Carlo estimation for the fraction of atoms undergoing a Sisyphus process. The Monte Carlo result is found to be of the same order as the simple analytical prediction (7). This is in apparent contradiction with the arguments presented at the end of Sec. I, according to which the probability for a Sisyphus process should increase: because of the van der Waals interaction, the atoms spend more time around the turning point and the spontaneous emission rate is enhanced. A close analysis of the dynamics in the Monte Carlo simulation reveals that, although these arguments are correct, the predicted increase is compensated by the sticking of a larger fraction of the atoms undergoing a Sisyphus process when the potential U_4 is replaced by $\overline{U}_4$.

The agreement between the Monte Carlo prediction for the fraction of cooled atoms and the experimental result is not as good as for the quantity t_{Sis}. It appears in Fig. 7 that the cooled fraction measured experimentally decreases less rapidly than the predicted one when the detuning δ is increased. For the detuning $\delta/2\pi=4.2$ GHz, the measured transition rate is two times greater than predicted. We did not find any definitive explanation for this discrepancy. It might be due to the presence of light scattered from the prism, because of surface irregularities. This extra light source could increase the rate of Raman processes, while not changing significantly the sharp exponential mirror potential.

IV. CONCLUSIONS

We have investigated an elementary step of Sisyphus cooling using cesium 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, provided the van der Waals interaction between the atom and the dielectric prism is taken into account. The importance of the van der Waals interaction for a quantitative description of the physics of the evanescent wave mirror has also been demonstrated by analyzing the fraction of bouncing atoms as a function of intensity and detuning [28].

This elementary Sisyphus process can be a convenient tool to accumulate a large number of atoms in a restricted domain of space, increasing therefore the quantum degeneracy of the gas. As pointed out in [16] and [18], the repetition of such processes, alternated 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 $\hbar^2k^2/2m$ 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 quasibidimensional gas [29–31]. This could provide an efficient way to prepare a 2D gas with a high quantum degeneracy.

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