Fast and efficient loading of a Rb magneto-optical trap using light-induced atomic desorption

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We have obtained fast loading of a rubidium magneto-optical trap and very high collection efficiency by capturing the atoms desorbed by a light flash from a polydimethylsiloxane film deposited on the internal surface of a cell. The atoms are trapped with an effective loading time of about 65 ms at a loading rate greater than 2×10^8 atoms per second. This rate is larger than the values reported in literature and is obtained by preserving a long lifetime of the trapped atoms. This lifetime exceeds the filling time by nearly two orders of magnitude. Trap loading by light-induced desorption from siloxane compounds can be very effectively applied to store and trap a large number of atoms in the case of very weak atomic flux or extremely low vapor density. It can be also effectively used for fast production of ultracold atoms.

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I. INTRODUCTION

Laser cooling and trapping of atoms in a magneto-optical trap (MOT) is a powerful and *world wide* used method to collect a large number of atoms at very low temperature. MOT is nowadays the main tool for many experiments in high-resolution laser spectroscopy, frequency standards, collision processes, quantum computing, atom optics [1], Bose-Einstein condensation [2,3] and, more recently, for precision tests of the standard model of weak interactions [4]. Several groups have trapped radioactive atoms in sight of studies of parity nonconservation effects [5,6] and of β decay [7–9].

Improvement of collection efficiency in a MOT is a key point for the experiments featuring very weak atomic flux or extremely low vapor density, which are normally produced by limited and expensive sources. The efficiency of a trap increases with the loading rate and decreases with the loss rate. Losses of the vapor owe to adsorption of nontrapped atoms at the cell walls and leaks through the port of the cell used for pumping and/or feeding the trap with atoms. Considerable collection efficiency of atoms has been demonstrated by using a vapor cell coated with dry film, which was shown to prevent atom adsorption on the walls of the cell. In a MOT for Cs with a dry-film-coated cell, Stephens and Wieman [10] and Guckert *et al.* [11] have achieved 6% and 20% collection efficiencies, respectively. The highest efficiency was demonstrated by Wieman and co-workers [6]: by using a quartz cell coated with dry film pumped by a very small orifice (2 mm in diameter) an efficiency of 56% was achieved.

In order to improve collection efficiency a pulsed atom source can be used, thus reducing the losses in the trap due to collisions of the trapped cold atoms with hot nontrapped atoms. Trap loading via pulsed atom sources has already been experimented. Fortagh *et al.* [12] and Rapol *et al.* [13] use a resistively heated Rb metal dispenser located very close to the trapping region. According to Ref. [13], Rb atoms are captured within few seconds at a loading rate of about 10^8 atoms per second, and the lifetime of trapped atoms exceeds the filling time by one order of magnitude. Anderson and Kasevich [14] modulate the Rb vapor pressure by light-induced atom desorption (LIAD). Here a light pulse illuminates the metallic surface of the cell to stimulate desorption of previously adsorbed atoms to obtain a 10 s loading time, i.e., a level equal to the trap lifetime.

In this work, loading a MOT through LIAD by a coated pyrex cell has been addressed. The effect exhibits a very high efficiency and does not demand for intense light. This makes it possible the illumination of a large portion of the cell surface and fast desorption of a considerably high amount of atoms. Moreover, the desorption dynamics is fast with respect to conventional thermal sources.

II. EXPERIMENTAL SETUP

Our MOT has a standard spherical design (see Fig. 1): the cell is made of a pyrex ball (10 cm in diameter), which is connected to an ionic pump through one-inch bottleneck and to a reservoir containing a small amount of metallic rubidium.

The reservoir yields a sufficiently high vapor density at room temperature to load the trap. The coating is made of polydimethylsiloxane (PDMS), a polymer featuring a very low adsorption coefficient, thus allowing many elastic collisions of the atoms onto the cell walls. The coating has also the property to collect a significant amount of atoms and to desorb them suddenly when illuminated [15–17]. The cell has been coated by following the standard procedure described in Ref. [16]. It is very important to remark that the coating does not appreciably affect the minimal pressure reachable in the apparatus. In fact, the residual background

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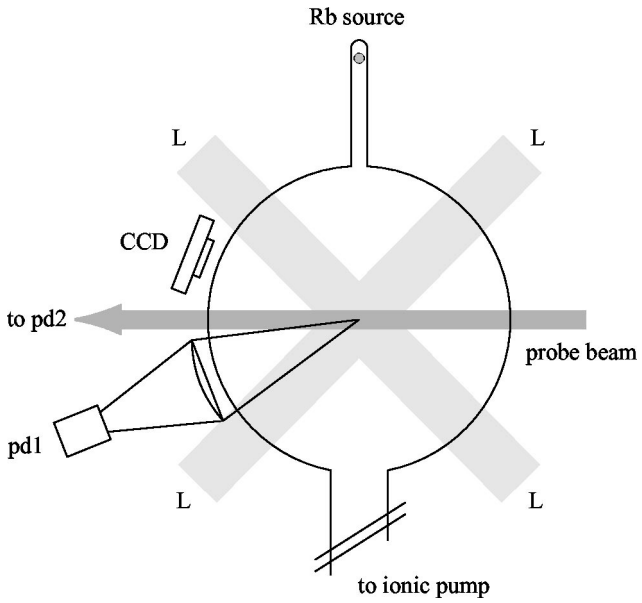

FIG. 1. A sketch of the experimental apparatus (top view). *L* stands for laser beams; pd1, pd2 stand for photodetectors.

pressure (1.7×10^{-10} mbar) measured nearby the cell is not affected by the presence of the coating. It is found anyway that the total background pressure suddenly increases after a light flash, then decreases back to equilibrium. The maximum background pressure can be controlled by light intensity. The number of Rb atoms desorbed at surface is proportional to the flash intensity over a wide range.

Two water-cooled coils provide a quadrupole magnetic field with a field gradient up to 30 G/cm. The laser for trapping is a Ti:sapphire ring laser, delivering a maximum power of about 300 mW at 780 nm. The laser is tuned 10 MHz below the $5S_{1/2}$, $F=3\rightarrow5P_{3/2}$, $F'=4$ closed transition of ^{85}Rb and is locked to a Fabry-Perot cavity, which is in turn actively locked to a frequency stabilized He-Ne laser. A free-running diode laser 10 mW in power tuned 10 MHz below the $5S_{1/2}$, $F=2\rightarrow5P_{3/2}$, $F'=3$ transition serves for repumping. The two laser beams are superposed and split into six beams, whose diameter is expanded to 1.8 cm by six telescopes. The fluorescence of the trapped atoms is imaged by a fast and calibrated photodetector equipped with an interferential filter. The signal is proportional to the number of cold atoms and is recorded by a digital scope, which is finally analyzed by a personal computer. Two charged-coupled device cameras monitor the size and shape of the cold atomic cloud with a spatial resolution of 200 μm. A second diode-laser beam (5 mm in diameter) monitors the time evolution of background rubidium density when the repumping laser is switched off. The absorption signal of the probe beam is measured by a fast photodetector located far away from the cell to minimize the disturbing signal from stray light of the flash. The flash (pulse duration about 1 ms) is a commercial device for photographic purposes.

III. ATOM LOADING IN A MOT

Optimization of loading efficiency in a MOT requires full knowledge of the processes involved. The system governing MOT loading can be conceived as an ensemble of a relatively warm gas of N_v nontrapped atoms containing a cold core of N_t trapped atoms—the MOT, strictly speaking. Loading is normally accomplished through feeding of atoms into population N_v at rate $I(t)$ by some external source. The process of loading is carried out through a time interval of τ seconds so that the total number of nontrapped atoms supplied is $\int_0^\tau I(t)dt$. The ensemble of atoms is not a closed system, so that atomic adsorption by the cell walls and loss through the port for pumping cause a continuous decrease in nontrapped atoms, which occurs at rate $-WN_v$, W being the waste coefficient.

Loading of the MOT results in a net transfer of nontrapped warm atoms to trapped cold atoms into the MOT by radiation pressure. This process occurs at rate LN_v, L being the loading coefficient. Indeed, since the potential of the MOT is considerably shallow, internal collisions between trapped atoms may cause a decrease in the population N_t, escaping from the trap at rate βN_t^2. Also scattering events of trapped Rb atoms with nontrapped Rb atoms may spill a net flux of trapped atoms at rate $\alpha N_t N_v$. Here α, β are proportionality constants. Finally, collisions with background gas may also waste trapped atoms at rate CN_t. In our case, just after the atom desorption, parameter C must be regarded as a time-dependent variable, $C(t)=C_0\exp(-Kt)+C_\infty$, the first term being ascribed to possible desorption of other molecules or atoms by LIAD and the second one due to the final residual gas pressure.

In summary, the set of equations governing the time evolution of N_v and N_t populations are

$$\frac{dN_t}{dt}=LN_v-C(t)N_t-\beta N_t^2-\alpha N_v N_t, \tag{1a}$$

$$\frac{dN_v}{dt}=-WN_v-LN_v+C(t)N_t+\beta N_t^2+\alpha N_v N_t+I(t) \tag{1b}$$

with the proper initial conditions for N_t and N_v.

In some cases, injection of atoms may be regarded as a relatively fast process with respect to time scale involved and hence N_0 atoms are supplied nearly instantaneously. Loading with LIAD meets this condition, since both the duration of flash and the intrinsic response time of LIAD are much faster than any other characteristic time in the experiment (see Fig. 2). Thereby, if LIAD is the only loading method involved, then it can be set $I(t)=N_0\delta(t)$ and $N_t(0)=0$, $N_v(0)=0$ in Eqs. (1), which is mathematically equivalent to $I(t)=0$ and $N_t(0)=0$, $N_v(0)=N_0$. Finally, our MOT is equipped with an additional source of atoms; in fact, Rb is supplied by a metallic reservoir hosted in a small appendix in the glass cell. Even though this latter is kept cold at liquid-nitrogen temperature during operation with the MOT, equilibrium between Rb atoms on the walls and the vapor phases occurs with no need for light excitation, liberating a constant but negligible flux of Rb vapor.

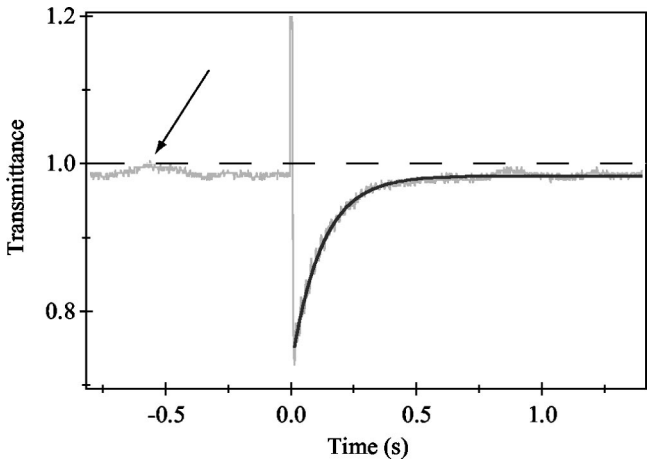

FIG. 2. Probe-laser absorption signal as a function of time detected in absence of magnetic field. The arrow indicates total transmission obtained by tuning the probe beam out of resonance for a short time. The spike at $t=0$ s is due to the stray flash light hitting the photodetector.

The loading efficiency η is a crucial parameter, quantifying the maximum number of trapped atoms, $N_t^{\max}$, vs the total number of atoms fed into the trap, $\int_0^\tau I(t)dt$,

$$\eta=\frac{N_t^{\max}}{\int_0^\tau I(t)dt}. \tag{2}$$

Under ideal conditions, namely, neglecting all scattering events that may partially deplete a MOT, i.e., $C=0$, $\alpha=0$, $\beta=0$, and considering a constant flux of atoms feeding the trap, $I(t)=I_0$, the number of trapped atoms grows proportionally with time after an initial transient:

$$N_t(t)=\frac{LI_0}{L+W}t.$$

The nature of the initial transient is determined by the initial conditions for N_t and lasts a time interval of the order of $1/(W+L)$, which is normally much shorter than τ for a cw loading.

Once loading is complete, i.e., at $t=\tau$, it holds $N_t^{\max}=N_t(\tau)=[LI_0/(L+W)]\tau$; it also comes out $\int_0^\tau I(t)dt=I_0\tau$, so that the loading efficiency when atomic collisions are neglected, η_{nc}, is

$$\eta_{nc}=\frac{L}{L+W}. \tag{3}$$

This is the formula determined in Ref. [6] for the cw loading used in that experiment. Indeed, the loading method concerned through this work is a sudden process and all the atoms are delivered at once at $t=0$, i.e., $N_v(0)=N_0$. Under ideal conditions $C=0$, $\alpha=0$, $\beta=0$, there comes out an exponential decay for the population of nontrapped atoms $N_v(t)=N_0e^{-(L+W)t}$ while the time evolution for the population of trapped atoms is $N_t(t)=[LN_0/(L+W)](1-e^{-(L+W)t})$. There being no loss in the trap, the maximum for $N_t(t)$ is attained after the loading transient at $t\gg 1/(L+W)$. When calculating efficiency according to Eq. (2), it turns out that Eq. (3) holds true also in this case. This result means that both techniques are potentially equivalent as far as noncollisional efficiency η_{nc} is concerned. In practical situations, Eq. (3) serves only as an upper limit because collision processes tend to void the trap ($\eta<\eta_{nc}$). Thus, under practical working conditions one should refer to Eq. (2), as will be done in the following.

The set of Eqs. (1) and the definition of efficiency in Eq. (2) have been modeled on our experiment though they appear to be of widespread application. In this way the ensemble of trapped and nontrapped atoms is treated as a dynamical system governed by Eqs. (1) in the form of ''rate equations.'' Nonlinear terms are also taken into account in Eqs. (1), which rule out any analytical approach to the solution. In the following section, we will focus on demonstrating that the time evolution foreseen by Eqs. (1) is experimentally accomplished and a measurement of the parameters involved will be drawn. It will also be possible to determine the relevance of nonlinear terms.

IV. RESULTS

A direct measurement of coefficient W can be carried out; if the trap is not under loading ($L=0$), then $N_t(t)=0$ all the time and Eq. (1b) holds:

$$N_v(t)=N_0e^{-Wt}. \tag{4}$$

Figure 2 shows the absorption signal due to the desorbed Rb atoms as a function of time at zero magnetic field. The experiment has been made with the rubidium reservoir cooled down to the liquid-nitrogen temperature in order to keep the rubidium vapor pressure as low as possible. The absorption signal increases very rapidly (characteristic time in the millisecond range) just after the flash pulse ($t=0$), followed by an exponential decay due to the atom losses, according to Eq. (4). The signal at $t<0$ corresponds to the absorption due to the residual rubidium vapor pressure before the light flash. The arrow indicates the total transmission of the probe beam, which is obtained by shifting the laser frequency out of resonance for a short-time interval. The best fit of the exponential decay is $W^{-1}=(125\pm 5)$ ms.

Trap loading via LIAD has been studied in detail on both a short and a long time scale. These two regimes are shown in Figs. 3 and 4, respectively. Figure 3(a) shows the signal detected by the photodiode after a flash pulse desorbing Rb atoms through LIAD. The magnetic field is set to zero and the laser is out of resonance. Except for the peak due to the flash light hitting the photodiode, no signal is detected. With all parameters kept unchanged, the laser is set on resonance and a signal appears as a result of fluorescence from desorbed atoms [Fig. 3(b)]. In this case the trap is not working. Finally, Fig. 3(c) shows a fluorescence signal from the MOT. The signal is averaged over 16 consecutive measurements in order to reduce the fluorescence fluctuations of cold atoms. This curve clearly shows that, just after the flash, the fluo-

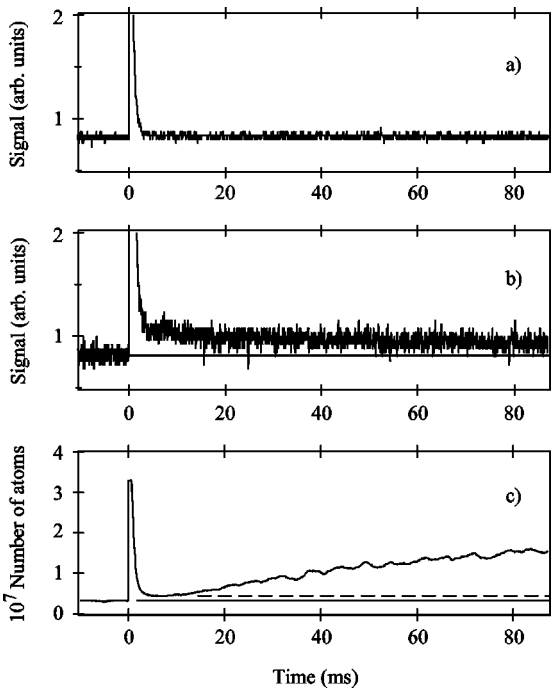

FIG. 3. Signal of the photodetector as a function of time; the spikes at $t=0$ s are due to the stray flash light. (a) flash light only, (b) flash with the laser frequency tuned to the resonance (no trap), (c) averaged fluorescence signal from trap. The dashed line indicates the contribution due to the fluorescence of nontrapped atoms.

rescence signal exhibits a sudden but relatively small increase due to the fluorescence of nontrapped atoms desorbed from the coating. This level (dashed line) equals that in Fig. 3(b). Then, after a delay of about 10 ms, the number of trapped atoms starts increasing and attains a considerably high value, $N_t=1.5\times10^7$, in a relatively short time (80 ms), leading to a high loading rate of about 2.0×10^8 s^{-1}.

An analysis based on a longer time scale has been carried out in Fig. 4 under the same conditions as for the measurements in Fig. 3. In order to reduce the fluctuations of fluorescence, an electronic low-pass filter, consisting of an *RC* circuit with time constant $\tau=300$ ms, was used. Curve *a*

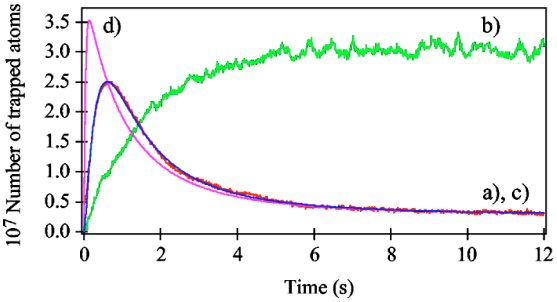

FIG. 4. Curve *a*, number of trapped atoms vs time with LIAD using a low-pass filter; the spike at $t=0$ has been removed from the curve; curve *b*, number of trapped atoms vs time for standard loading (no LIAD); curve *c* is the fit of curve *a* through integration of Eqs. (1) taking into account the effect of the filter. The curve is nearly indistinguishable from curve *a*; curve *d*, number of trapped atoms vs time if no filter was present.

illustrates the experimentally recorded fluorescence signal of trapped atoms. After the flash, the fluorescence signal rapidly increases with time, attains a maximum at $N_t=2.5\times10^7$, then slowly falls off. For comparison, the fluorescence signal of a conventionally loaded trap is shown in Fig. 4, curve *b*, under same experimental parameters for the trap. It comes clear that the LIAD technique allows the trap loading to be by far faster than for the conventional technique. The reason for the decrease in fluorescence in the case of the LIAD technique owes to the waste of trapped atoms. In curve *b*, Fig. 4, the number of trapped atoms keeps constant at long time because feeding with atoms is carried continuously. In this latter case, if the laser is switched off, fluorescence decays with the same time constant as it takes to saturate. It is important to remark that in our experiment the trap lifetimes are comparable for both loading methods.

The experimental curve *a* in Fig. 4 has been fit by solving Eqs. (1) under the simplifying assumption $\alpha=\beta=0$, which will be reconsidered later. Indeed, the assumption $\beta=0$ was used in previous work by Anderson and Kasevich [14]. In the determination, it has been assumed the previously measured value $W=8$ s^{-1}; another constraint is given by the condition that at very long time it holds $\dot{N}_v(+\infty)=\dot{N}_t(+\infty)=0$, which leads to $C_\infty=LI/[WN_t(+\infty)]$. The fit also includes the effect of the electronic filter.

Curve *c* in Fig. 4 is the result of the fit, which is in very good agreement with experimental data. In fact curve *c* and curve *a* of Fig. 4 are nearly indistinguishable. Accordingly, it comes out that the initial number of atoms desorbed via LIAD is $N_0=6.5\times10^7$ atoms and the loading coefficient is $L=15$ s^{-1}, which corresponds to an effective loading time $1/L=65$ ms. The value for the C coefficient is $C(t)=[2.9\exp(-0.38t)+0.038]$ s^{-1}, and $I=1.8\times10^4$ atoms/s. Figure 4, curve *d*, shows the number of trapped atoms vs time when the effect of the filter, which is not sufficiently fast to follow the rapid raising time of fluorescence in the case of LIAD, is removed. When this effect is taken into account, there comes out a value $N_t^{\max}=3.5\times10^7$ atoms at $t=0.140$ s. The uncertainties over the parameters of the fit are lower than 5% except that for C_∞ and I, which are about 60%. However, such two large uncertainties are not relevant for the discussion as will be shown in Fig. 5. The slope of curve *d* in Fig. 4 in the early stage of trap loading is the loading rate as measured if there was no filter. It comes out as 2.5×10^8 atoms/s, in agreement with the measured value in Fig. 3.

Equation (2) is the general definition of efficiency, which can be written in the case of LIAD loading as

$$\eta=\frac{N_t^{\max}}{\int_0^\tau I(t)\,dt}=\frac{N_t^{\max}}{N_0}=(54\pm7)\%.$$

Such efficiency is comparable with the best previous determinations [6,10,11] in spite that no special attention has been paid to reduce the loss rate. Previous determinations

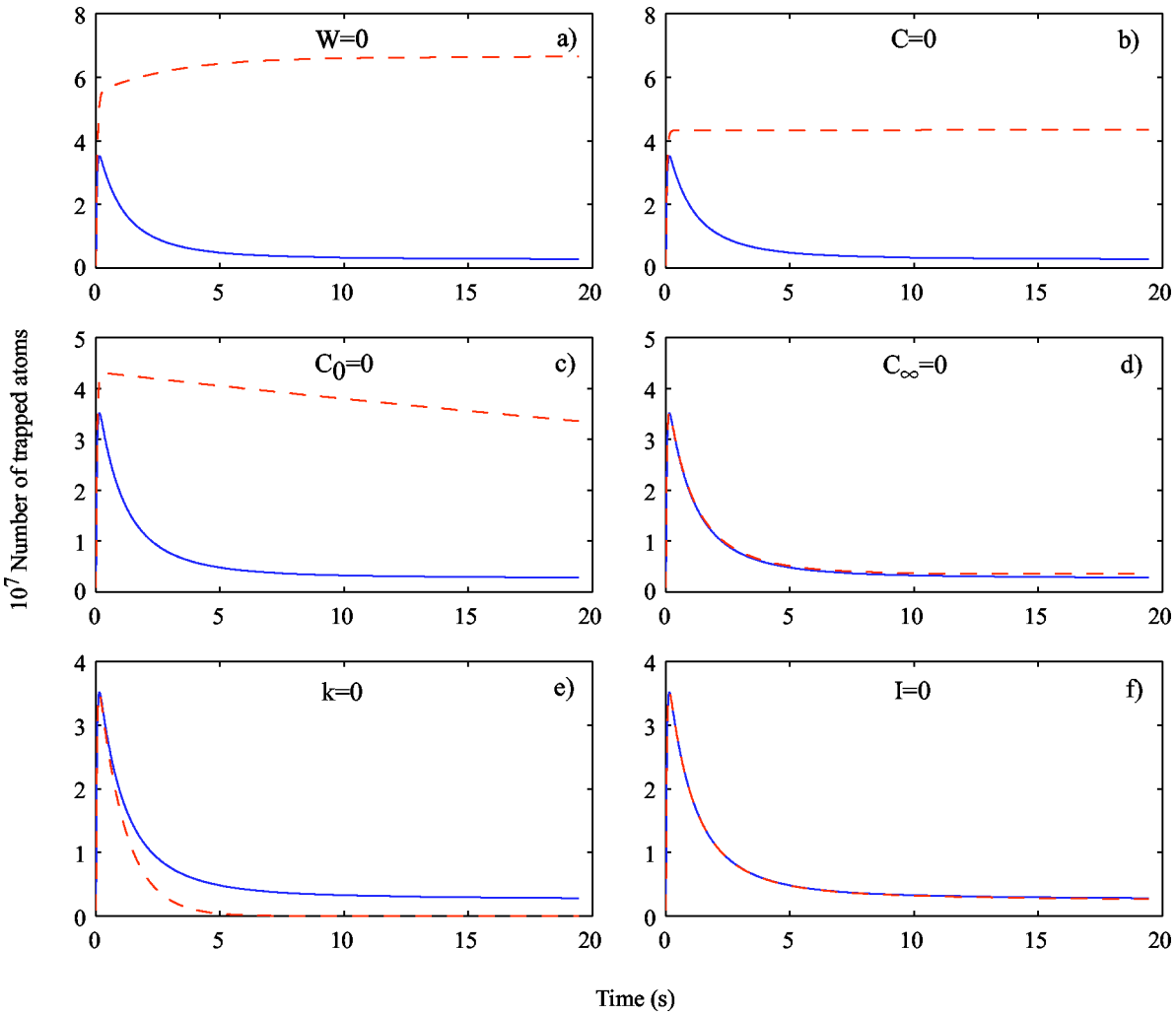

FIG. 5. Time evolution of the number of trapped atoms determined by computer simulation by suppressing a term at a time in Eqs. (1) (dashed line), compared with the complete solution (solid line). (a) $W=0$, (b) $C=0$, (c) $C_0=0$, (d) $C_\infty=0$, (e) $k=0$, and (f) $I=0$.

used Eq. (3) as a quantifier of the capability to trap atoms; for comparison the noncollisional efficiency is calculated also in our case:

$$\eta_{nc}=\frac{L}{L+W}=65\%,$$

which is a value greater than those obtained by previous experiments.

In order to check the assumption made over α and β, we repeated the fit leaving these parameters as free. Indeed, we observed no appreciable change in the other parameters of the fit while negligible values for α and β were determined. The reason for $\beta\simeq 0$ is compatible with the level of density of trapped Rb atoms we used and consistent with the previous determination made by Anderson and Kasevich [14] under similar experimental conditions. Collisions between trapped atoms with nontrapped atoms occur at rate $\alpha N_v N_t$: indeed the lifetime of nontrapped atom population is e folded in $1/W=125$ ms so that such a collisional term is relevant only over a time interval that is short with respect to the time scale involved in the experiment. In any case, the major role for the decay in the population N_t is established by collisions of trapped atoms with the molecules of residual gas and those desorbed through LIAD.

The good agreement between the measurements and the results of simulation allows an in-depth analysis of each individual term in Eqs. (1). Figure 5 shows the time evolution of fluorescence of trapped atoms by suppression of each term in Eqs. (1) and comparison with the previously determined complete solution. For $W=0$ [Fig. 5(a)] there is no waste of atoms out of the cell and the long-term populations of trapped and nontrapped Rb atoms owe to equilibrium. Initially, the curve increases with a characteristic time owing to loading of the trap, i.e., the term LN_v dominates. Then, once the trap has been sufficiently populated, the collisional term prevails ($LN_v \ll CN_t$), and the curve saturates at a value slightly lower than $N_0=6.5\times 10^7$ with a characteristic time $1/k$. For $C=0$ [Fig. 5(b)] the curve saturates at a level lower than in the previous case because the waste term W voids the number of nontrapped atoms in the cell. This demonstrates that a good way to increase the number of trapped atoms would be to reduce the W term, for example, by using a small port separating the cell from vacuum system, as was

experimentally done in Ref. [6]. Figure 5(c) ($C_0=0$) and Fig. 5(d) ($C_\infty=0$) show that the loss of trapped atoms due to collisions with the background gas desorbed from the coating through LIAD is dominant with respect to the collisions with the final residual gas. Figure 5(e) ($k=0$) is a further demonstration that a constant term C cannot be used to interpret experimental evidences, because the background gas desorbed through LIAD is strongly time dependent. Figure 5(f) shows that the constant source term I, due to the presence in the cell of Rb atoms coming from the cold metallic reservoir or from the walls in absence of desorbing light, is completely negligible.

V. CONCLUSIONS

In summary, a MOT has been loaded with Rb atoms emitted from a PDMS coated cell through LIAD. We have demonstrated that such a technique allows a significant improvement in the loading rate with respect to standard loading from a vapor at thermal equilibrium. By using the PDMS coating we have obtained an effective loading time of 65 ms., i.e., about two orders of magnitude shorter than the values reported in literature. Moreover, this time is about two orders of magnitude shorter than the trap lifetime. As a consequence, considerable improvement in the loading efficiency has been recorded. The reason for the high value of trapping efficiency and simultaneously fast atom trapping owes to emission from a source extending 4π sr in solid angle. However, the dramatic increase in the loading rate may call forward further effects such as the generation of a subthermal distribution of desorbed atoms through some mechanisms such as the one proposed in Ref. [18]. Further investigation must be done for full understanding. This methodology can be effectively applied to store and trap a large number of atoms in the case of very weak atomic flux or extremely low vapor density. Moreover, the development of the rapid loading of MOTs that maintains a reasonably long lifetime is important to the fast production of ultracold atoms such as alkali Bose-Einstein condensates with a single vapor cell trap.

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