Dependence of loading time on control parameters in a standard vapour–loaded magneto–optical trap*

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Loading time is one of the most important dynamic characteristics of a magneto–optical trap. In this paper, we primarily report on a detailed experimental study of the effects of some magneto–optical trap control parameters on loading time, including the background vacuum pressure, the magnetic field gradient, and the intensities of trapping and repumping lasers. We compare the results with previous theoretical and experimental results, and give qualitative analysis. These experimental investigations offer some useful guidelines to control the loading time of magneto–optical traps. The controllable loading time achieved is helpful to enhance the signal-to-noise ratio of photoassociation spectroscopy, which is remarkably improved from 7 to 28.6.

Keywords: cold atoms, loading time, magneto–optical trap

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1. Introduction

Optical cooling and trapping techniques are becoming increasingly prevalent in a variety of physics experiments and are continually being adapted to an ever-broader range of experimental needs.[1−3] Experiments in Bose–Einstein condensation (BEC) and ultracold molecules both particularly require the atoms to be efficiently loaded into a magneto–optical trap (MOT). The loading process is a slow dynamic equilibrium determined by a loading rate and an atom trap loss rate.[4,5] The time to reach the equilibrium state in the process of loading is called "loading time". The study of the loading time, as one of the important dynamics characteristic of an MOT, not only helps to understand the dynamic behaviour of ultracold atomic collision, but also provides a chance to optimize the experimental measurements based on MOTs. For instance, the evaporative cooling techniques used to achieve BEC rely on loading a large number of atoms into a magnetic trap with a long trap lifetime.[6] Large numbers of atoms and long lifetimes were achieved by working with a long loading time.[7] However, precision spectroscopy entails a short loading time to obtain high detection sensitivity in the experiments of cold atom photoassociation.[8]

In the process of the actual operation of an MOT for cold atoms, MOTs can be operated in very different conditions, which are dominated by different mechanisms.[9] There is no quantitative model to determine the dependence of loading time on MOT parameters. Usually, the loading time was considered to be related to some experimental parameters in the MOT, such as background vacuum pressure, magnetic field gradient, and the intensity of trapping and repumping lasers.[10,11] However, how the loading time varies with these parameters is poorly understood. A detailed experimental study of how to control the loading time has never been made. In this paper, we present a detailed experimental study of the loading time of a Cs atom MOT. The experimental data demonstrate that loading time is independent of the intensities of trapping and repumping lasers in a cer-

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tain range, but dependent on vacuum pressure and magnetic field gradient. The theoretical model based on the cold atom loading rate equation is used to accurately predict the loading time for all MOT parameters. According to the data and theoretical analysis, we find that the background vacuum pressure and magnetic field gradient are inversely proportional to the loading time. These results provide a guideline to control loading time by changing the vacuum pressure and the magnetic field gradient in an MOT.

2. Experimental approach

The experimental setup is schematically shown in Fig. 1. The sample of cold atoms was prepared in a standard vapour-loaded Cs MOT as described in Ref. [10]. The mental vacuum chamber is connected with a Cs getter source and an ion pump. The background pressure can be continuously changed by the value of the ion pump and is measured by use of a high precise vacuum meter (937A Gauge Controller). The magnetic field gradient ($\mathrm{d}B/\mathrm{d}z$) in the centre of the trap is produced by a pair of quadruple coils and the stray magnetic fields are removed by using three orthogonal pairs of compensating coils. The magnetic field gradient of the trap is changed by controlling the current of the coils. The temperature of the cold atomic sample is estimated to be ∼200 μK by the time of flight method. The trapping and repumping lasers are provided by two frequency-stabilized diode lasers (DL100, Toptic) with line widths of less than 1 MHz by using a standard saturated absorption technology. The trapping laser frequency is about two natural linewidth red detuned from the $6S_{1/2}$ $(F = 4) \rightarrow 6P_{3/2}$ $(F' = 5)$ atomic transition. The repumping laser is locked to the transition of $6S_{1/2}$ $(F = 3) \rightarrow 6P_{3/2}$ $(F' = 4)$, which stimulates population in the $6S_{1/2}$ $(F = 3)$ level back to the $6S_{1/2}$ $(F = 4)$ level. The cold atom fluorescence is collected by a convex lens and detected through an avalanche photodiode (Hamamatsu Si APD, S3884).

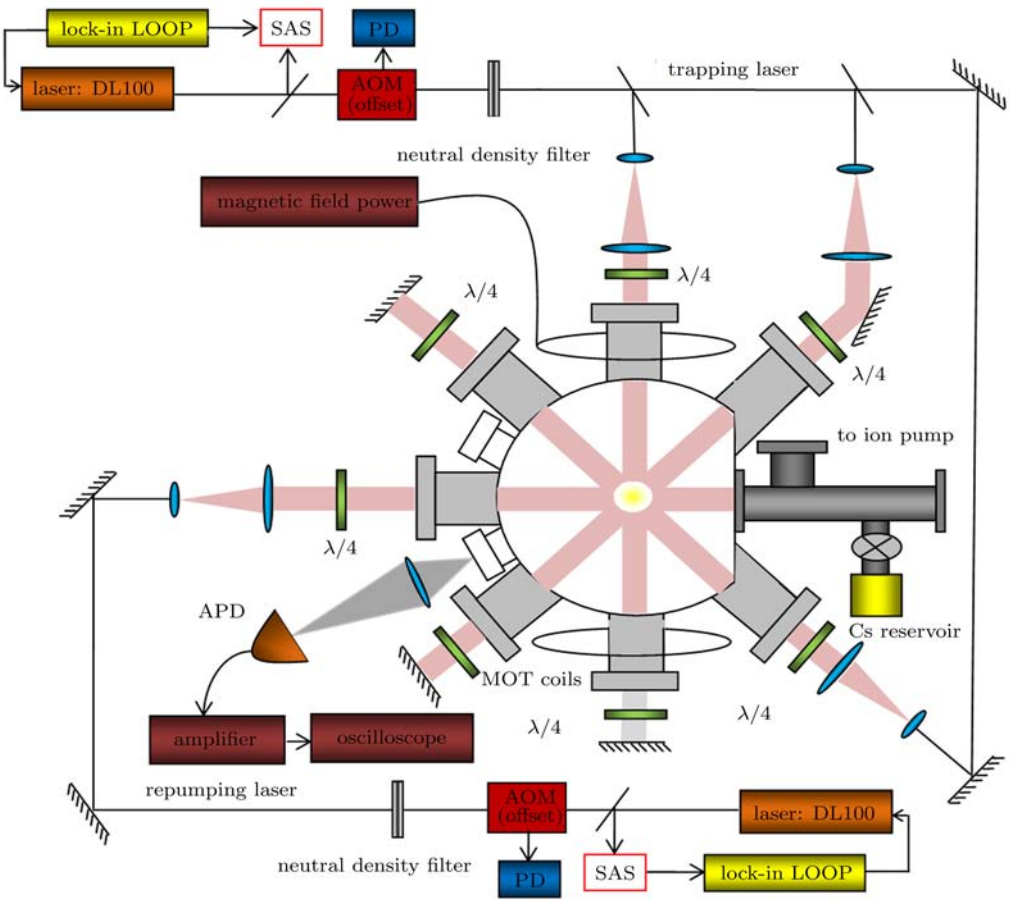


Fig. 1. (color online) Experimental setup for trapping of cold atoms in an MOT. SAS is saturation absorption spectrum. The arms of the MOT which are perpendicular to the plane of the figure are omitted for clarity.

In our experiment, we control the loading process by turning off and on the acoustic–optical modulator (AOM). By using a photodiode (PD), the laser beam split out by AOM can be probed.

3. Theory

The number of cold cesium atoms in the MOT, $N(t)$, can be described by a rate equation[10]

$$\frac{\mathrm{d}N}{\mathrm{d}t} = R - N\left(\frac{1}{\tau_{\mathrm{Cs}}} + \frac{1}{\tau_{\mathrm{b}}}\right) - \beta\int_v n_{\mathrm{c}}^2(r,t)\mathrm{d}^3r, \quad (1)$$

where N is the number of trapped atoms, R is the trap loading rate, $n_{\mathrm{c}}(r,t)$ is the density of cold cesium atoms in the MOT, the second term on the right-hand side of Eq. (1) represents trap-loss rate due to the collisions between the trapped atoms and background gas. N/τ_{Cs} is the trap-loss rate caused by the collisions of trapped cold Cs atoms with those untrapped background thermal Cs atoms, while N/τ_{b} refers to the trap-loss rate caused by the collisions of trapped cold Cs atoms with background of residual noncesium atoms. However, Cheng *et al.*[12] pointed out that the probability of trapped atom collision with a similar atom is larger than that with heterogeneous atom, thus the term N/τ_{b} can be neglected. The last term in Eq. (1) represents the density-dependent trap-loss rate which can be neglected as the atom number is low in the trap ($\beta = 0$).[13] We find that the number of steady-state atoms is about 1×10^7 by absorption technology, which satisfies the above-mentioned approximation.

As the cold cesium atoms in the MOT reach a certain number ($N \geq 10^4$), the cold atoms will absorb scattering photons radiated from other cold atoms. The repulsion energy of cold atoms is too large to be neglected. Thus the density of the cold atomic cloud is a constant but the trap volume enlarges as the atom number increases. In our experiment, we find that the number of steady0state atoms is about 1×10^7 by absorption technology. Let n_{c} be the density of cold atoms, then rate Eq. (1) will turn into

$$\frac{\mathrm{d}N}{\mathrm{d}t} = R - \frac{N}{\tau_{\mathrm{Cs}}}. \quad (2)$$

At the initial condition $N(0) = 0$, rate equation (2) can be solved as

$$N = N_{\mathrm{s}}\left(1 - e\frac{-t}{\tau_{\mathrm{Cs}}}\right), \quad (3)$$

where $N_{\mathrm{s}} = R\tau$ is the number of steady state atoms. The trap loading rate R can be obtained from the theory of gas molecule movement in statistical physics as[11]

$$R = \frac{n_{\mathrm{b}}V^{2/3}v_{\mathrm{c}}^4}{2a^3} = \frac{1}{2}n_{\mathrm{b}}Sv_{\mathrm{c}}^4\left(\frac{m}{2k_{\mathrm{B}}T}\right)^{3/2}, \quad (4)$$

where n_{b} is the density of background atoms, V is the trapping volume, S is the effective surface area of the MOT, $\alpha = (2k_{\mathrm{B}}T/\mathrm{m})^{1/2}$ is the most probable speed, v_{c} is the capture speed of cold atoms, m is the mass of Cs atom, k_{B} is the Boltzmann constant and T is the temperature of the environment. We presume

$$n_{\mathrm{b}} \propto \left(\frac{\mathrm{d}B}{\mathrm{d}z}\right)\frac{P}{k_{\mathrm{B}}T}$$

to be the density of background atoms, where P is the background vapour pressure, $\mathrm{d}B/\mathrm{d}z$ is magnetic field gradient. $1/\tau_{\mathrm{Cs}}$ is the loss rate from the trap and it is due primarily to collisions with atoms in the MOT, which determines the number of trapped atom collisions per unit time until they escape from the MOT, so the trap-loss rate is

$$\begin{aligned}\frac{1}{\tau_{\mathrm{Cs}}} &= n_{\mathrm{b}}\sigma v_{\mathrm{rms}} \\ &= n_{\mathrm{b}}\sigma\sqrt{3k_{\mathrm{B}}T/m} \propto \left(\frac{\mathrm{d}B}{\mathrm{d}z}\right)P\sigma\sqrt{\frac{3}{mk_{\mathrm{B}}T}}, \quad (5)\end{aligned}$$

where σ is the collision cross section of background atoms impacting trapped cold atoms out of the MOT. v_{rms} is the root-mean-square velocity of the background atoms.

The loading time of cold atoms in the MOT can be expressed as[10,14]

$$\tau_{\mathrm{Cs}} = \frac{1}{n_{\mathrm{b}}\sigma v_{\mathrm{rms}}} \propto \frac{1}{\left(\frac{\mathrm{d}B}{\mathrm{d}z}\right)P\sigma}\sqrt{\frac{mk_{\mathrm{B}}T}{3}}, \quad (6)$$

where

$$n_{\mathrm{b}} \propto \left(\frac{\mathrm{d}B}{\mathrm{d}z}\right)\frac{P}{k_{\mathrm{B}}T}$$

is the density of Cs_2 atoms, σ is the collisional cross section of the background atoms with trapped cold atoms, v_{rms} is the root-mean-square velocity of the background atoms, m is the mass of Cs atom (2.2×10^{-25} kg), k_{B} is the Boltzmann constant (1.38×10^{-23} J/K), T is the temperature of background vapour (300 K), σ is the collision cross section of the background cesium atoms (2×10^{-13} cm^2).[15] Thus, we can demonstrate that loading time τ_{Cs} is independent of trapping and repumping laser power,

but dependent on vacuum pressure and magnetic field gradient. From Eq. (6), we can find that loading time $\tau_{\rm Cs}$ is inversely proportional to vacuum pressure P and magnetic field gradient $\mathrm{d}B/\mathrm{d}z$.

4. Experimental results and discussion

In order to study experimentally the dependence of loading time on controllable parameters, we change the one of these parameters, while the remaining parameters are kept unchanged. In order to change the trapping laser intensity, we place neutral density filters in the setup. Repumping laser intensity can also be varied by neutral density filters. Figures 3–5 illustrate how the loading time of the trapped atoms varies with the MOT parameter. We find that the loading time is quite sensitive to vacuum pressure and magnetic field gradient. Trapping and repumping laser intensities are varied in a certain range, during which a stability of the density of Cs atoms and trap volume is achieved. The stability is necessitated in the study of cold atoms. The loading process is shown in Fig. 2. The loading time $\tau_{\rm Cs}$ is obtained when loading process reaches $1/e$ of the final equilibrium. In our experiment, loading time can be directly obtained through fitting the loading curves by using Eq. (6) in Origin software.

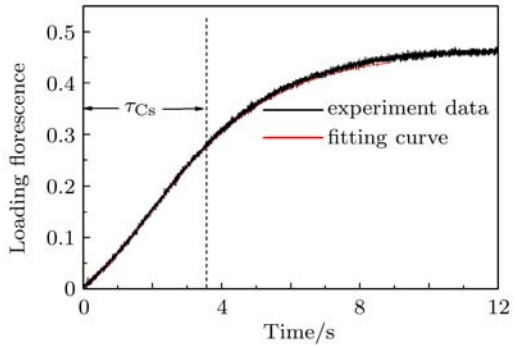


Fig. 2. (color online) The loading curves with the vacuum pressure of 3×10^{-7} Pa, the magnetic field gradient of 10 Gs/cm, the intensity of trapping lasers of 18 mW/cm^2 and the intensity of repumping lasers of 4.5 mW/cm^2.

Figure 3 shows how the loading time varies with vacuum pressure when the magnetic field gradient is 10 Gs/cm (1 Gs = 10^{-4} T), the intensity of the trapping laser is 18 mW/cm^2, and the intensity of the repumping laser is 4.5 mW/cm^2. The vacuum pressure in the MOT is changed by using a controlling ion pump. As vacuum pressure changes from 1.4×10^{-7} Pa to 5.3×10^{-7} Pa, the loading time decreases from 6.8 s to 2.0 s. The black solid squares denote the experimental data. The solid line represents the theoretical fitting curve according to Eq. (6), which shows a good agreement between the experimental results and the theoretical curve in Fig. 2. The error bars indicate the range of $\tau_{\rm Cs}$ values that are obtained from the varying of the density of Cs atoms, thereby giving the experimental uncertainty. Changing the vacuum pressure leads to the variation of density of background Cs atoms.

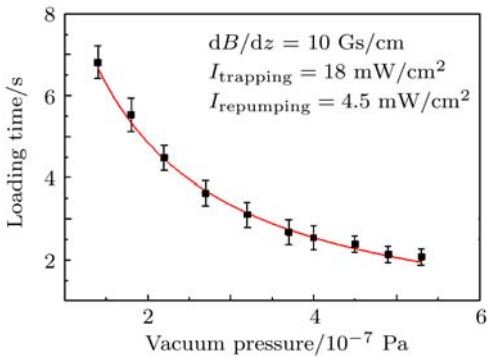


Fig. 3. (color online) Systematic study of the effect of vacuum pressure on the loading time measurements. The black solid squares denote the experimental data. The solid curve refers to the theoretical fitting according to Eq. (6).

Figure 4 shows that the loading time decreases as the gradient of magnetic field increases, when other parameters are fixed. These parameters are given when the vacuum pressure is 3×10^{-7} Pa, the intensity of the trapping lasers is 18 mW/cm^2, and the intensity of the repumping laser is 4.5 mW/cm^2. The gradient of the magnetic field in the MOT is changed by adjusting the current in the magnetic field coils. As the magnetic field gradient varies from 2.67 Gs/cm to 13.3 Gs/cm, the loading time decreases from 5.5 s to 2.1 s. The black solid squares with vertical error bars represent the experimental data. The solid line refers to the theoretical predictions. The experimental data and the theoretical predictions are in good agreement with each other. The vertical error bars indicate the range of $\tau_{\rm Cs}$ values that are obtained from the varying of the density of Cs atoms, which are from the experimental uncertainty. Changing the magnetic field gradient leads to a variation of Cs atoms density.

Finally, as the intensities of trapping and repumping lasers increase, with vacuum pressure being 3×10^{-7} Pa and magnetic field gradient being 10 Gs/cm, the loading time approximately keeps unchanged, which is also shown in Fig. 5. The black

solid squares with vertical error bars denote the experimental data and solid line represents the linear fitting. The results demonstrate that loading time is independent of trapping and repumping laser power, which has been analysed by the theory we proposed. The values of $\tau_{\rm Cs}$ are obtained from the changing of the trap volume of cold atoms, given the experimental uncertainty. Changing the number of trapped atoms leads to the variation of trap volume.[16] Frequency dither of the trapping laser leads to the variation of trapped atom number. In our experiment, a standard saturated absorption technology is used to stabilize line-width of trapping and repumping laser less than 1 MHz.

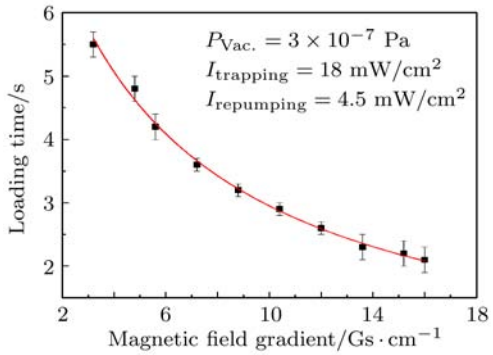


Fig. 4. (color online) Systematic study of the effect of magnetic gradient on the loading time measurements. The black solid squares denote the experimental data. The solid curve refers to the theoretical fitting according to Eq. (6).

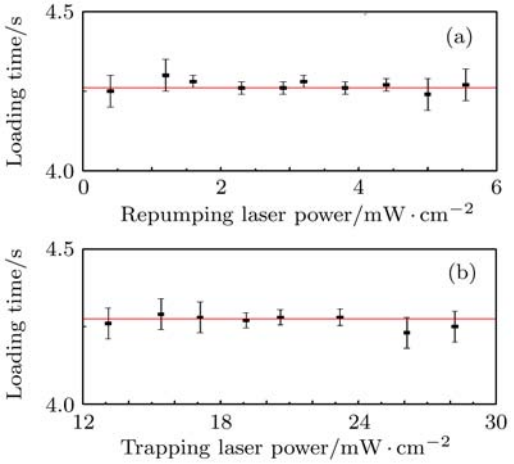


Fig. 5. (color online) (a) The loading time of trapped atoms as a function of the repumping laser power. The black solid squares denote the experimental data and solid line refers to the linear fitting. (b) The loading time of trapped atoms versus the trapping laser power. The black solid squares denote the experimental data and the solid line refers to the linear fitting. The vacuum pressure and the magnetic field gradient are 3×10^{-7} Pa and 10 Gs/cm, respectively.

We qualitatively analyse the dependence of loading time on the controllable parameters in the MOT above by comparing the experiment data with the results from the theoretical model. These experimental studies provide some guidelines to control the loading time of the MOT. Loading time can be controlled by changing vacuum pressure and magnetic field gradient. As vacuum pressure and magnetic field gradient increase, the loading time decreases inversely.

In order to study the relationship between the loading time and the signal-to-noise ratio (SNR) of the photoassociation spectrum, we change the vacuum pressure to investigate the variation of the SNR of the photoassociation spectrum, as shown in Fig. 6.

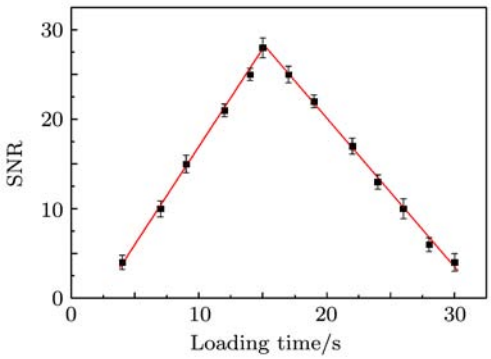


Fig. 6. (color online) Systematic investigation for the dependence of the spectral SNR on the loading time. The largest SNR 28.6 is achieved while the loading time is 15 s.

The uncertainty is due mainly to the fitting and the statistic error of several measurements. The maximum SNR ∼28.6 of spectra is obtained when the loading time is 15 s. Figure 7 shows a typical spectrum for vibrational quantum number $v = 17$ of $0_{\rm g}^-$ pure long-range state, whose detuning is ∼51 cm^{-1} compared with $6P_{3/2}$ dissociation limit. The maximum SNR of

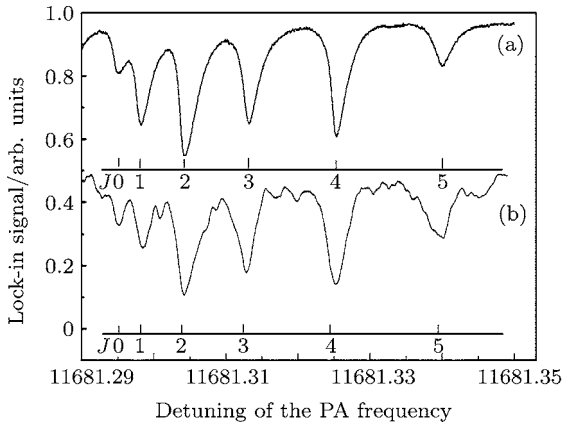


Fig. 7. (color online) Photoassociation spectra for $v = 17$ of Cs_2 $0_{\rm g}^-$ pure long-range state with different loading times each as a function of PA laser detuning. The loading time is 15 s and 3 s for (a) and (b) respectively.

spectroscopy is up to 28.6 with suitable loading time (15 s), with a loading time randomly chosen as 3 s by controlling the experimental parameters, an SNR value as low as 7 is displayed in the lower panel. Compared with the good result with an SNR value of 28.6, a controllable loading time is beneficial for the PA experiment.

5. Conclusion

We reported on the results of the loading time in an MOT. By using the rate equation, the variations of loading time in an MOT with vacuum pressure, magnetic field gradient, intensity of trapping and repumping laser are comprehensively analysed. The experimental results demonstrated that loading time is independent of trapping and repumping laser power, but dependent on vacuum pressure and magnetic field gradient. According to the experimental data and theoretical analysis, we find that the background pressure and the magnetic field are both inversely proportional to the loading time. These experimental studies offer guidelines to control the loading time of an MOT, thus a remarkably improved SNR (∼28.6) of PA spectrum is achieved with loading time being 15 s. The experiment result we achieved is conducible to further research on, for example, the simulation of Raman transition to produce ultracold ground-state molecules.

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