Loading of atoms into an optical trap with high initial phase-space density

Kosuke Shibata, Shota Yonekawa, and Satoshi Tojo

Department of Physics, Chuo University, 1-13-27 Kasuga, Bunkyo, Tokyo 112-8551, Japan
(Dated: November 29, 2016)

We report a method for loading cold atoms into an optical trap with high initial phase-space density (PSD). By simply overlapping the trap beam with atoms in optical molasses, $4 \times 10^9$ rubidium atoms with an initial temperature less than 10 µK are loaded into a single beam trap. The estimated initial PSD exceeds 0.01, which is several orders greater than that achieved with the conventional loading method. The proposed method is promising for creating a quantum gas with a large number of atoms in a short evaporation time.

PACS numbers:

I. INTRODUCTION

An optical trap is one of the most useful tools in cold-atom experiments [1, 10]. It can hold atoms regardless of their spin, whereas a magnetic trap can hold only atoms in low-field-seeking states. Owing to this advantage, the optical trap has enabled the study of collisional properties between different spin states [2, 3] or spinor Bose-Einstein condensates (BECs) [4, 5]. Another advantage of optical traps is the high flexibility for spatial shapes in the trap. Trap potentials of various shapes, including box-shaped trap potentials [7], can be created via suitably designed optical traps. Optical traps also enable dynamical shape change using a lens on a moving stage [8], an acousto-optic modulator (AOM) [9], and a focusable lens [10]. Moreover, evaporative cooling in an optical trap requires a shorter time compared to that in a magnetic trap owing to the tight confinement in optical traps. The short evaporation time enables a high repetition rate in experiments and relaxes the requirement for a high vacuum, which is mandatory for achieving a long trap time. In addition, the evaporative cooling in optical traps is indispensable for creating quantum degenerate gases of atoms having no electric spins such as alkaline-earth (like) species (for example, [11, 12]).

The simple and most popular strategy to produce quantum degenerated gases through an all-optical method (that is, without magnetic traps) has been the initial loading of many atoms from a magneto-optical trap (MOT) into a deep trap produced by a high-power beam. Although the atoms get heated during the loading and their initial temperature is higher than that in MOTs, the trapped atoms can be cooled via successive evaporation. If the initial number of atoms in the trap is sufficient, the atoms reach quantum degeneracy with evaporative cooling. A BEC containing $10^4$ or $10^5$ atoms is typically produced when a few million bosonic atoms are initially loaded into an optical trap with an evaporative cooling time of several seconds [13, 14]. A larger quantum degenerate gas will be created in a shorter evaporation time if the initial temperature can be decreased. Kinoshita et al. [14] reported the production of a BEC with $3.5 \times 10^5$ atoms through the evaporative cooling in an optical trap in 1 s with pre-cooling in an optical lattice before loading the optical trap.

We report a simple and effective method for loading many well-cooled atoms in an optical trap. The loading is performed by overlapping the beam with atoms in optical molasses. Four million atoms are loaded into a single-beam optical trap with a beam waist of 28 µm and depth of 1 mK. The initial temperature of loaded atoms is found to be less than 10 µK, while the conventional loading method is accompanied by heating, which makes the temperature settle to $\sim 1/10$ of the trap depth [14]. Owing to the high density and low temperature, the estimated initial PSD exceeds 0.01, which is several orders of magnitude greater than that obtained with the conventional loading method.

II. EXPERIMENTAL SETUP

We prepare cold $^{87}$Rb atoms in a vacuum glass cell using a MOT in the independent six $\sigma^+\sigma^-$ beam configuration. The cooling beam is detuned by $\Delta_M = -20$ MHz from the $5^2S_{1/2} F = 2$ to $5^2P_{3/2} F' = 3$ transition and the repump beam is resonant to the $F = 1$ to $F' = 2$ transition. The cooling and repump beams are output from an optical fiber, expanded to a beam radius of 8 mm, and divided into six beams with equal power. The powers of the cooling and repump beams output from the fiber are 120 mW and 1.7 mW, respectively. The peak intensities at the cell (summed over all beams) are $I_M = 110$ mW/cm$^2$ and $I_R = 1.5$ mW/cm$^2$, respectively, considering the power loss at the cell. A pair of coils in the anti-Helmholtz configuration generates a magnetic-field gradient of 11 G/cm (along the coil axis) for the MOT. We typically collect $2 \times 10^8$ atoms in the MOT within 20 s.

After collecting atoms, we compress the MOT by using the following standard method. We increase the field gradient to 25 G/cm in 10 ms and decrease the repump...
beam intensity $I_R$ to 10 $\mu$W/cm$^2$ in another 10 ms. During the decrease of repump beam intensity, $\Delta_M$ is swept to $-32$ MHz by changing the RF frequency applied to an AOM in the cooling beam path.

We turn off the magnetic-field gradient within 1 ms after the compression and start the polarization gradient cooling (PGC), which consists of two parts. In the first part, $\Delta_M$ is swept from $-32$ MHz to $-80$ MHz and $I_M$ is decreased to 1/4 of the initial intensity in 10 ms while $I_R$ is kept constant. The second part starts with a frequency jump of the laser locking point from the $F' = 3$ peak to the $F' = 2$ - 3 crossover peak. This jump shifts $\Delta_M$ by $-133$ MHz and enables large detuning. The frequency jump is achieved within 600 $\mu$s, during which no significant diffusion of atoms is observed. The parameters of the cooling and repump beam (intensity and detuning) are optimized to achieve better loading into the optical trap, as described later. The cooling in the second part lasts for 2.5 ms. After the second part, 1.8 x 10$^8$ atoms at less than 10 $\mu$K are typically produced with cancellation of the residual magnetic field using three coil pairs for generating conditions that allow effective PGC. The coil currents are finely adjusted to maximize the atom number in the optical trap. We estimate the residual field to be less than 50 mG.

The optical trap beam is turned on after the atom cloud is cooled with the cooling and repump beams kept on. The trap beam is generated from a Ti:S laser and is red-detuned from the $D_2$ line by 1.2 THz. The beam is passed through an AOM for intensity control and delivered to the cell via an optical fiber. The beam waist is $w = 28 \mu$m, and the beam is focused in molasses. Further, the beam is linearly polarized along the horizontal axis. The beam power is set at the maximum value of 190 mW, unless otherwise indicated. The maximum potential depth is calculated to be $k_B \times 1.0$ mK.

The molasses and the optical trap beam are overlapped for 30 ms, unless otherwise indicated. The loading of atoms is completed in this short period, as described later. After the loading, we shut off the cooling and repumping beams and hold atoms in the optical trap for 25 ms, during which the atoms in the molasses fall off and are separated from the optical trap. During the holding, the atoms are irradiated by a weak pumping beam, and almost all atoms are pumped to the $F = 1$ state. We measure the atom number and temperature through absorption imaging after the time of flight.

III. DEPENDENCE OF LOADING ON MOLASSES PARAMETERS

We investigate the dependence of the loading on molasses beam parameters such as the intensity and detuning of the cooling and repump beams. The molasses parameters during the second PGC part and the loading are changed when taking the following data.

We first focus on the dependence of the atom number and temperature on the cooling beam detuning $\Delta_M$. The atom number increases with increasing $\Delta_M$, as shown in Fig. 1(a). The repump beam intensity and detuning are fixed during this measurement to $I_R = 8 \mu$W/cm$^2$ and $\Delta_R = +20$ MHz, respectively, which are optimal values for the loading, as shown later. The atom number peaks around $\Delta_M = -205$ MHz with $I_M = 34$ mW/cm$^2$. The data with larger $\Delta_M$ are not taken owing to technical limitations. Because the frequency separation between the $F' = 2$ and 3 states is 266 MHz, the undesirable heating of atoms may occur for such a large detuning of approximately $-200$ MHz, where the laser frequency is close to the $F = 2$ - $F' = 2$ resonance. In addition, the AC stark effect in the optical trap shifts the resonance frequency by + 40 MHz for the deepest trap; consequently, the laser frequency becomes even closer to the $F = 2$ - $F' = 2$ resonance. Nevertheless, no significant heating is observed, as shown in Fig. 1(b). The temperature is approximately 14 $\mu$K for any $\Delta_M$ in the measured range. We infer that the $F = 2$ - $F' = 2$ transition does not lead to heating, because it quickly pumps atoms into the $F = 1$ state. The emergence of the dark state may assist the pumping.

The cooling beam power mainly influences the temperature. We observe the increase in the temperature to approximately 18 $\mu$K for $I_M = 55$ mW/cm$^2$. This suggests that the temperature is dominantly determined by the PGC, the temperature decrease by which is predicted to be proportional to $I_M/\Delta_M$. Despite the difference in temperature, the number of loaded atoms for $I_M = 38$ mW/cm$^2$ and $I_M = 55$ mW/cm$^2$ are comparable in the achievable detuning range. Thus, $I_M = 38$ mW/cm$^2$ results in a larger PSD. The following experiments are performed with $I_M = 38$ mW/cm$^2$ and $\Delta_M = -205$ MHz. The result, as discussed later, implies that the molasses...
temperature has little influence on the loading efficiency.

It should be noted that the low temperature of the atoms in the optical trap demonstrated here is quite striking. The temperature is much less than 1/50 of the trap depth $U=k_B \times 1.0 \text{ mK}$, while the conventional loading method is usually accompanied with the heating of atoms (an initial temperature $T \sim U/4$ has been reported \cite{17}). Considering the deformation of the trap due to the scattering force \cite{15}, the net potential depth is $U=k_B \times 700 \mu K$, and $T$ is still much less than $U/10$. The absence of the magnetic-field gradient in our case is supposed to be essential for achieving a low temperature. PGC is homogeneous in our scheme, unlike loading from a MOT, in which the magnetic-field gradient degrades PGC. A typical field gradient of 10 G/cm prevents the cooling in the optical trap with the waist of only a few tens of µm.

The atom number in the optical trap also depends on the repump beam intensity $I_R$ and detuning $\Delta_R$. Fig. 2 shows the atom numbers in the optical trap for different repump parameters. As in the case of loading from the MOT \cite{17}, the atom number is maximized when the repump beam parameters $I_R$ and $\Delta_R$ are weak and near zero, respectively. It can be seen in Fig. 2(a) that the profile becomes broader when the beam intensity is increased from $I_R=9.7 \mu W/cm^2$ to $19 \mu W/cm^2$, with the peak atom number decreased. A dip around the resonance is observed for a beam of $I_R=39 \mu W/cm^2$. This result suggests that an excessive repumping rate leads to the atom loss. The decrease in the atom number with the increase of $I_R$ is most probably related to the light-assisted collisional loss, as discussed in detail in \cite{17}. The optimal $\Delta_R$ is approximately $+20 \text{ MHz}$. The difference from the resonance can be explained by the AC Stark shift in the optical trap, which makes the resonance frequency increase by a few tens of MHz.

We also investigate the optimal intensity at a fixed frequency of $\Delta_R = +20 \text{ MHz}$. The result is shown in Fig. 2(b). The optimal beam intensity is $\approx 8 \mu W/cm^2$, which is slightly less than that used when acquiring the data in Fig. 2(a). The atom number decreases for increasing $I_R$, as expected from the previous result. For low intensities, the atoms in the molasses are observed to fall because of gravity. We suppose this sets the limit on the minimum repump intensity in our setup.

**IV. LOADING DYNAMICS**

Fig. 3 shows the loading curves for three different trap depths. The trap depths (and the corresponding trap beam powers) are 1.0 mK (190 mW), 770 µK (140 mW), and 600 µK (110 mW). The cooling and repump beam parameters are $I_M=34 \text{ mW/cm}^2$, $\Delta_M=-205 \text{ MHz}$, $I_R=9.7 \mu W/cm^2$, and $\Delta_R = +20 \text{ MHz}$. As the atom number reaches a few millions within 20 ms, the loading rate is roughly estimated to be higher than $10^8$ atoms/s. The solid lines are fitting curves based on the simple loading model described below. The gradual decrease in the atom number is attributed to the molasses lifetime and collisional losses. The large maximum atom number indicates that the loading rate exceeds the molasses loss rate and the collisional loss rate in the trap. Although one might expect the loading from the optical molasses to be inefficient because of the diffusion of the molasses, the extremely high loading rate enables us to load several million atoms from the molasses into the trap.
The time dependence of the atom number in the optical trap $N$ can be described by

$$\frac{dN}{dt} = R_0 \exp(-\gamma_M t) - \beta' N^2, \quad (1)$$

where $R_0$ is the initial loading rate and $\gamma_M$ and $\beta'$ are the loss rate of the molasses and the two-body loss coefficient, respectively [17]. We omit the one-body loss term because it is negligible in the concerned time scale. We also neglect the three-body collisional loss term for the simplicity of the discussion. The model in Eq. (1) fits the experimental data. The fitted parameters are plotted as a function of the trap beam power $P$ in Fig. 4. As shown in Fig. 4(a), the loading rate $R$ ranges from $4 \times 10^8$ atoms/s to $6 \times 10^8$ atoms/s. The rates are more than 10 times higher than that achieved by loading directly from the MOT, in which case $R$ is approximately $3 \times 10^7$ atoms/s when the trap depth is $\sim 1 \text{ mK}$ [17].

The high loading rate is considered have resulted from the high density of molasses of $n = 1.1 \times 10^{12} \text{ cm}^{-3}$ because the loading rate depends on atom flux into the optical trap, which is proportional to $nv$ ($v$: the atom velocity). Although $nv$ is almost constant in the sub-Doppler regime [19], we suspect that the $v$ of an atom entering the trap is determined by the trap potential depth $U_0$, independent of $n$. Because the molasses loss rate is much less than $U_0/k_B$, the conversion of a fraction of $U_0$ to kinetic energy determines the $v$ of an atom entering the trap. The fact that the observed loading rate is proportional to $\sqrt{P}$, as shown in Fig. 4(a), supports the inference that a fraction of $U_0$ is converted to $v$. The high damping coefficient in PGC is another possible reason for the increase of the loading rate. As a large damping coefficient leads to the overdamping of atom motion in the trap, an atom entering the trap is expected to be trapped with a high trapping probability.

The values of the fitted two-body loss coefficients shown in Fig. 4(b) are comparable to the results in [17]. As already discussed in [17], the two-body loss is mainly caused by light-assisted collisions. The observed increase in $\beta'$ with the increase of $P$ is reasonable because the light-assisted collision loss rate is proportional to the inverse of the trap volume and a large $P$ leads to tight confinement. The molasses loss rate $\gamma_M$ is approximately $140 \text{ s}^{-1}$ for any $P$, which is consistent with the decrease of the number of atoms in the molasses.

V. INITIAL TEMPERATURE AND PHASE-SPACE DENSITY

In order to measure the initial temperature $T_0$ immediately after the completion of loading, the heating due to the photon scattering of the trap beam during the holding time should be taken into account because the small detuning of $-1.2 \text{ THz}$ from the $D_2$ line leads to a high photon scattering rate.

We determine $T_0$ by extrapolating the temperatures measured for holding times of 25, 27.5, 30, 32.5, and 35 ms, as shown in Fig. 5(a). The data are taken for $I_M = 34 \text{ mW/cm}^2$, $\Delta_M = -205 \text{ MHz}$, $I_R = 8 \text{ mW/cm}^2$, and $\Delta_R = +20 \text{ MHz}$. Assuming a constant heating rate, the fitted values of $T_0$ and the heating rate when the trap beam power $P = 190 \text{ mW}$ are $8.7 (1.5) \mu\text{K}$ and $0.23(5) \mu\text{K/ms}$, respectively. The measured heating rate is consistent with the value estimated from the trap beam intensity and detuning. The data for different $P$ values are similarly analyzed, and the estimated $T_0$ values are shown in Fig. 5(b). The initial temperatures $T_0$ are less...
than 10 μK for any $P$ and, on average, around 8 μK.

The fact that $T_0$ is comparable to the molasses temperature supports the idea that PGC determines $T_0$. More precisely, it is supposed that $T_0$ is determined by $k_B T_0 = (D_1 + D_2)/\alpha$, where $D_1 = (\hbar k_i)^2 \Gamma_1$ and $D_2 = (\hbar k_i)^2 \Gamma_2$ are the diffusion coefficients of the molasses and the trap beams, respectively, with $k_i (i = 1, 2)$ being the wavenumber and $\Gamma_i$ being the photon scattering rate. $\alpha$ is the damping coefficient of the cooling, approximately given by $30/17(\hbar k_i)^2 \Gamma/\Delta_M$ where $\Delta_M$ is much greater than the natural line width $\Gamma$ according to the PGC theory for $\sigma^+\sigma^-$ beams [20]. Based on this consideration, we fit the data by $T_0^0 + aP$ to obtain $T_0^0 = 5.0 (1.4)$ μK and $a = 22 (18)$ nK/mW. Although $a$ is estimated to be approximately 1 nK/mW from the scattering rate of the trap beam, the large $a$ is acceptable considering the imperfection of the cooling.

The initial low temperature in the optical trap of tight confinement naturally leads to a high PSD. For example, the atom number and temperature after a holding time of 25 ms at $P = 190$ mW are $N = 4.0(5) \times 10^6$ and $T = 14(1)$ μK, respectively, which leads to a peak PSD of $\rho = 0.03$, assuming atoms equally populate the $F=1$ sub-levels. This $\rho$ is several orders of magnitude greater than that in the loading from the MOT, which typically gives $\rho \sim 10^{-4}$ or $10^{-5}$. The PSD immediately after the holding is expected to be even higher. The estimation based on $N$ and the initial temperature $T_0$ obtained above provides a peak PSD of 0.06. It is noted that the true initial PSD is greater than this estimation because the initial atom number $N_0$ is reduced to $N$ during the holding time.

In order to take advantage of this high initial PSD, it is desirable to suppress heating and atom loss after loading. In particular, we need to reduce the three-body collisional loss because the cold atoms in the trap of tight confinement have an extremely high peak density ($\propto n^3 T^{-3/2}$, $n$ : mean trap frequency). In fact, the peak density in the deepest trap is estimated to be as high as $7 \times 10^{14}$ cm$^{-3}$, which leads to the high three-body collisional loss rate [21]. We find that the sudden decrease in the trap beam power after the loading can be a countermeasure against the high density. By reducing the trap beam power to 1/3 of the initial value in 1 ms after the loading, 3.7(1) $\times 10^6$ atoms of $T = 7.3 (2)$ μK are left after holding for 25 ms. Although the PSD decreases slightly, it maintains a high value of 0.02. This is a good start point for the evaporation because the loss and heating of atoms are suppressed in the trap of reduced power.

VI. SUMMARY AND OUTLOOK

We successfully loaded a large number of atoms with low temperature in an optical trap by simply overlapping molasses and the trap beam. The loading is optimized when the beam detuning due to molasses is approximately $-200$ MHz, and the loaded atoms are cooled to a temperature less than 1/10 of the trap depth. Despite the short molasses lifetime, the optimized loading enables the molasses atoms to be loaded into the optical trap efficiently within the lifetime of the molasses.

The high initial PSD is advantageous for reducing the evaporation time. A short evaporation time is helpful for experiments requiring a high repetition rate. The reduction in the evaporation time also decreases the loss during the evaporation, including the loss due to collision with the hot background atoms. Thus, the high initial PSD will enable one to create a quantum gas in a rough vacuum environment. This is particularly suitable for hybrid experiments combining cold atoms with other systems. The fast evaporation might also open the possibility of evaporative cooling in an optical trap of a moderate detuning, as was used in this work.

A larger atom number is also expected when using a trap having a larger volume combined with the loading from the molasses. A large trap volume mediates the collisional loss and leads to small $\beta'$, which should increase the atom number (approximately $\propto \sqrt{R/\beta'}$). With a trapping beam of higher power, it is feasible to increase the trap beam size by a factor of 2 while maintaining the trap depth. Noticing that the trap volume is proportional to $\nu^4$, the loading of $2 \times 10^7$ atoms is expected in such a trap. As the atom loss during the evaporation from $\rho = 0.02$ to the critical value of $\rho_c = 2.6$ for the BEC transition is estimated to be 50 % according to the scaling law [22], the entirely optical production of a BEC with more than $1 \times 10^6$ atoms is expected, while all-optical BECs created previously contain at most around $10^6$ atoms, even with the trap beam of 58 W and the elaborate dynamical beam-size change [9]. In particular, the use of high-power infrared laser is promising because the low photon scattering rate in it is appropriate for evaporative cooling. The reduced heating may also lead to a lower initial temperature. Such a large BEC in an optical trap is suitable for many experiments including multi-component and spinor BEC experiments [3, 4].

The loading method demonstrated here should be applicable to other experiments of cold atoms, and alkali atoms in particular, because no additional lasers nor changes in the MOT paths are required. The method will broaden the applications of cold atom gases owing to its capability of producing ultracold or quantum degenerate gases of large number of atoms in a short time.

Acknowledgments

We would like to thank T. Hibino, N. Ichinoseki, and S. Fujita for their assistance in constructing the earliest experimental setup. This work was supported by the Matsuo Foundation; the Research Foundation for Opto-Science and Technology; Grant-in-Aid for Scientific Research (Nos. 26887033, 15K05234, 23740308) from the Ministry of Education, Culture, Sports, Science, and Technology of Japan; and Chuo University Joint Research Grant.
[1] R. Grimm, M. Weidemuller, and Y. B. Ovchinnikov, Advances In Atomic, Molecular, and Optical Physics 42, 95 (2000).
[2] S. Tojo, T. Hayashi, T. Tanabe, T. Hirano, Y. Kawaguchi, H. Saito, and M. Ueda, Phys. Rev. A 80, 042704 (2009).
[3] D. M. Stamper-Kurn and M. Ueda, Rev. Mod. Phys. 85, 1191 (2013).
[4] D. S. Hall, M. R. Matthews, J. R. Ensher, C. E. Wieman, and E. A. Cornell, Phys. Rev. Lett. 81, 1539 (1998).
[5] J. Stenger, S. Inouye, D. M. Stamper-Kurn, H.-J. Miesner, A. P. Chikkatur, and W. Ketterle, Nature 396, 345 (1998).
[6] M.-S. Chang, C. D. Hamley, M. D. Barrett, J. A. Sauer, K. M. Fortier, W. Zhang, L. You, and M. S. Chapman, Phys. Rev. Lett. 92, 140403 (2004).
[7] A. L. Gaunt, T. F. Schmidutz, I. Gotlibovych, R. P. Smith, and Z. Hadzibabic, Phys. Rev. Lett. 110, 200406 (2013).
[8] T. L. Gustavson, A. P. Chikkatur, A. E. Leanhardt, A. Görlitz, S. Gupta, D. E. Pritchard, and W. Ketterle, Phys. Rev. Lett. 88, 020401 (2001).
[9] R. Roy, A. Green, R. Bowler, and S. Gupta, Phys. Rev. A 93, 043403 (2016).
[10] J. Léonard, M. Lee, A. Morales, T. M. Karg, T. Esslinger, and T. Donner, New Journal of Physics 16, 093028 (2014).
[11] Y. Takasu, K. Maki, K. Komori, T. Takano, K. Honda, M. Kumakura, T. Yabuzaki, and Y. Takahashi, Phys. Rev. Lett. 91, 040404 (2003).
[12] A. Griesmaier, J. Werner, S. Hensler, J. Stuhler, and T. Pfau, Phys. Rev. Lett. 94, 160401 (2005).
[13] M. D. Barrett, J. A. Sauer, and M. S. Chapman, Phys. Rev. Lett. 87, 010404 (2001).
[14] K. Arnold and M. Barrett, Optics Communications 284, 3288 (2011).
[15] S. Kumar, S. Hirai, Y. Suzuki, M. Kachi, M. Sadgrove, and K. Nakagawa, Journal of the Physical Society of Japan 81, 084004 (2012).
[16] T. Kinoshita, T. Wenger, and D. S. Weiss, Phys. Rev. A 71, 011602 (2005).
[17] S. J. M. Kuppens, K. L. Corwin, K. W. Miller, T. E. Chapp, and C. E. Wieman, Phys. Rev. A 62, 013406 (2000).
[18] S. Chu, J. E. Bjorkholm, A. Ashkin, and A. Cable, Phys. Rev. Lett. 57, 314 (1986).
[19] C. G. Townsend, N. H. Edwards, C. J. Cooper, K. P. Zetie, C. J. Foot, A. M. Steane, P. Szriftgiser, H. Perrin, and J. Dalibard, Phys. Rev. A 52, 1423 (1995).
[20] J. Dalibard and C. Cohen-Tannoudji, J. Opt. Soc. Am. B 6, 2023 (1989).
[21] E. A. Burt, R. W. Ghrist, C. J. Myatt, M. J. Holland, E. A. Cornell, and C. E. Wieman, Phys. Rev. Lett. 79, 337 (1997).
[22] K. M. O’Hara, M. E. Gehm, S. R. Granade, and J. E. Thomas, Phys. Rev. A 64, 051403 (2001).