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Excessive levitation for the efficient loading of large-volume optical dipole traps*

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We study the excessive levitation effect in the magnetically levitated loading process of ultracold Cs atoms into a large-volume crossed optical dipole trap. We analyze the motion of atoms with a non-zero combined gravito-magnetic force during the loading, where the magnetically levitated force catches up with and surpasses the gravity. We present the theoretical variations of both acceleration and velocity with levitation time and magnetic field gradient. We measure the evolution of the number of trapped atoms with the excessive levitation time at different magnetic field gradients. The dependence of the number of atoms on the magnetic field gradient is also measured for different excessive levitation times. The theoretical analysis shows reasonable agreement with the experimental results. Our investigation illustrates that the excessive levitation can be used to reduce the heating effect of atoms in the magnetically levitated loading process, and to improve the loading rate of a large-volume optical dipole trap.

Keywords: ultracold Cs atoms, optical dipole trap, magnetic levitation

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1. Introduction

Microscopically confining and trapping neutral cold atoms is a well-developed technique, and it represents a valuable tool for fundamental and applied research in ultracold experiments.[1–3] Optical dipole traps (ODT) consisting of focused far-off resonance laser beams have the advantage of being able to confine atoms in any magnetic sublevel for long periods of time without inducing heating from scattered photons.[4,5] They have been widely used for the creation of both Bose–Einstein condensates (BEC)[6,7] and quantum degenerate Fermi gases,[8,9] as well as Feshbach resonances.[10,11] Ultracold atoms can be loaded into a variety of ODTs with many particular geometric configurations, which allows us to construct numerous physical situations such as crossed-laser-beam waveguides,[12] double-well potentials,[13,14] and shaken-optical lattices.[15] In many contexts, loading as many atoms as possible into an ODT is one of the main prerequisites.

Limited by the laser power, the potential of a large-volume ODT is inevitably shallow and comparable to the gravitational potential for the atoms.[7] An essential requirement for efficiently loading atoms is that the temperature of the atomic sample must be sufficiently lower than the trap depth of the ODT. Many elaborate strategies have been used to obtain an atomic sample at low temperature.[16,17] Meanwhile, magnetic levitation, which is usually implemented by applying a magnetic field gradient to compensate for the gravity, is employed to cancel the gravity-induced anti-trapping potential. Particularly for atoms with large masses, magnetic levitation has been employed as a vital step in a few experiments that include ^{133}Cs and ^{87}Rb BEC obtained in an optical trap,[7,18] accelerated evaporative cooling for Cs BEC,[19] and the measurement of Feshbach resonances for the interspecies ^{6}Li–^{133}Cs.[20] These studies are, however, limited to cancelling the gravity and forming an efficient trapping potential using an optimized magnetic field gradient and a uniform bias field. An easily-ignored process, where the magnetic force begins to increase but has not yet compensated for the gravity completely, should be considered for more efficient loading. During this non-equilibrium process, the residual gravity always accelerates the atoms, and thus induces heating of the atomic sample.

Although some studies on the influence of gravity for ultracold atoms in magnetic and optical traps,[7,19,21,22] both the loading with the non-equilibrium gravito-magnetic force and its dynamics in the magnetic levitation-associated loading process for the ODT have not yet been investigated in detail. Fur-

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ther the magnetic levitation without heating are required for many potential applications, such as cold atoms on a chip[23,24] and the guiding of cold atoms.[25] In this paper, we study the heating effect for ultracold Cs atoms in the non-equilibrium, magnetically levitated loading process. The excessive levitation is employed for suppressing the heating, and an efficient loading of a large-volume crossed ODT is obtained. Variations of both acceleration and velocity are theoretically analyzed with respect to the levitation time and the magnetic field gradient. The dependences of the number of trapped atoms on the excessive levitation time and the magnetic field gradient are measured and show reasonable agreement with the theoretical analysis.

2. Theoretical model

During the loading of a large-volume crossed ODT, the gravity of Cs atom induces a large destructive potential, which has a strength similar to the optical trapping potential in the vertical direction.[7,19] The magnetic levitation method has been employed to cancel the anti-trapping potential for an efficient loading of the ODT, where the magnetic force induced by a magnetic field gradient is used to compensate for the gravitational force in the vertical direction z.[21] The magnetic field gradient $B' = \partial B/\partial z$ is produced by a pair of anti-Helmholtz coils with a resistor-inductor circuit. The variation of B' with time t can be described as

$$B'(t) = B'_0(1 - \mathrm{e}^{-t/\tau}), \tag{1}$$

where B'_0 is the objective magnetic field gradient, and τ is the characteristic time, which can be obtained by measuring the evolution of B' as shown in Fig. 1.

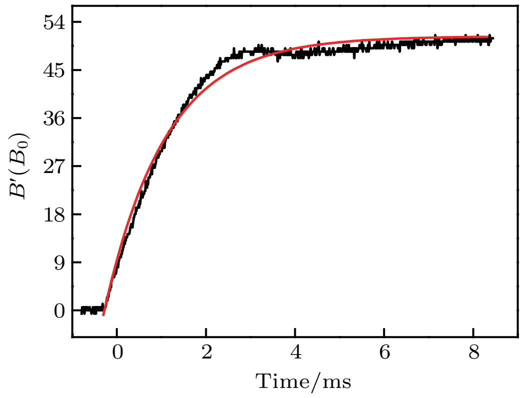

Fig. 1. (color online) Magnetic field gradient B' in the vertical direction as a function of time. The characteristic time was determined to be 1.2 ms by applying Eq. (1) to the variation of B' with time.

In the magnetically levitated loading process, the combined gravito-magnetic force at time t is given by

$$F(t) = F_0(1 - \mathrm{e}^{-t/\tau}) - mg, \tag{2}$$

where F_0 is the magnetic force when $B' = B'_0$, m is atomic mass, and g is the gravitational acceleration. The magnetic force can be expressed as $F_0 = mgB'_0/B'_\mathrm{G}$, and B'_G is the magnetic field gradient when magnetic force completely compensates for the gravity. The variable acceleration of the atoms in the vertical direction can be expressed as

$$a(t) = g\frac{B'_0}{B'_\mathrm{G}}(1 - \mathrm{e}^{-t/\tau}) - g. \tag{3}$$

The atomic velocity can be given by

$$v(t) = \int_0^t a\,\mathrm{d}t = g\frac{B'_0}{B'_\mathrm{G}}(t + \tau\mathrm{e}^{-t/\tau} - \tau) - gt. \tag{4}$$

The velocity mentioned in this paper refers to the velocity that the atoms obtain in the magnetically levitated loading process of the crossed ODT.

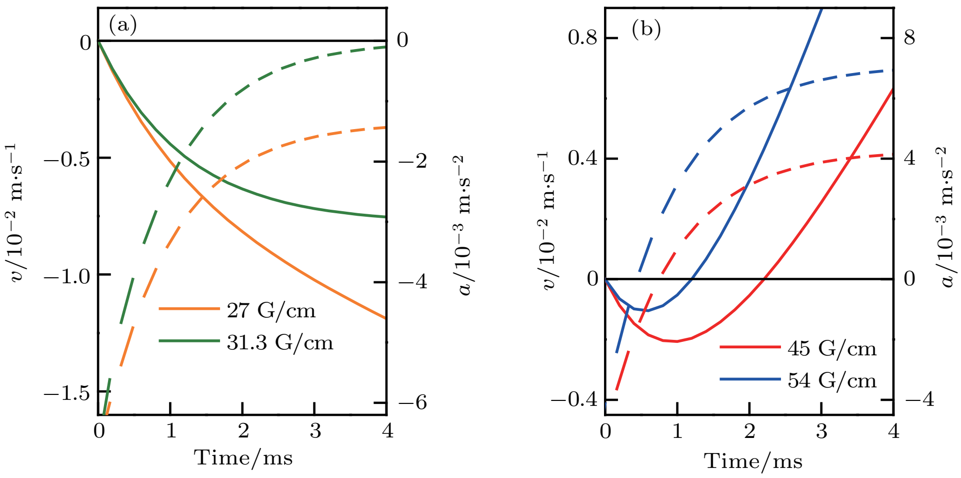

Fig. 2. (color online) Atomic velocity (solid lines) and acceleration (dashed lines) as a function of levitation time at the magnetic field gradients of (a) $B'_0 = 27$ G/cm (orange line), 31.3 G/cm (green line), (b) 45 G/cm (red line), and 54 G/cm (blue line).

For Cs atoms in the hyperfine state $F = 3$, $mF = 3$, B'_G is given as $B'_G = 31.3$ G/cm.[21] Variation of the atomic acceleration $a(t)$ (dash lines) and the atomic velocity $v(t)$ (solid lines) at different B'_0 are shown in Fig. 2. Before the increasing magnetic force cancels out the gravity, the downward atomic velocity increases with time, while the downward acceleration reduces. As time goes on, for the gradients $B'_0 \leq 31.3$ G/cm in Fig. 2(a), the acceleration becomes saturated and the velocity keeps going down. If we apply the critical levitated field gradient of $B'_0 = 31.3$ G/cm, then the atomic sample experiences the heating effect due to the obtained downward velocity. However, for the excessively levitated field gradients of $B'_0 > 31.3$ G/cm shown in Fig. 2(b), there is a zero point for acceleration when the downward atomic velocity achieves its maximum. Afterwards, the downward velocity decreases towards zero, and then the atoms have a continuously increasing upward velocity with an increasing upward acceleration. Thus, to suppress the heating effect, we can use an excessively levitated gradient and immediately change it to the critical value of $B'_G = 31.3$ G/cm at the time that satisfies $v(t) = 0$.

3. Experimental setup

^{133}Cs atoms are cooled and trapped in a standard vapor-loaded magneto-optical trap (MOT). Following the compressed MOT and the optical molasses cooling, an enhanced 3D degenerated Raman sideband cooling (DRSC)[16] is performed to prepare Cs atomic sample with a number of 1×10^7 atoms in the desired state $6S_{1/2}$, $F = 3$, $mF = 3$ at a temperature of ~ 2.0 μK. We load the atoms prepared by 3D DRSC into a larger-volume crossed ODT, which is constructed by using 1070 nm, collimated multiple-longitudinal-mode, linearly polarized beam from a Yb:fiber laser.[21] As shown in Fig. 3, the laser output is divided into two beams that are weakly focused on the center of the collection of atoms at an angle of 90°. The laser beam powers are 7.0 W and 7.2 W, and the corresponding trap-center beam waists are $w_x = 230$ μm and $w_y = 240$ μm, respectively. For each laser beam, an acousto-optical modulator is used for intensity stabilization and rapidly switching off beam in less than 1 μs. To prevent any interference between the two laser beams, one is downshifted in frequency by 110 MHz, while the other is upshifted by 110 MHz.

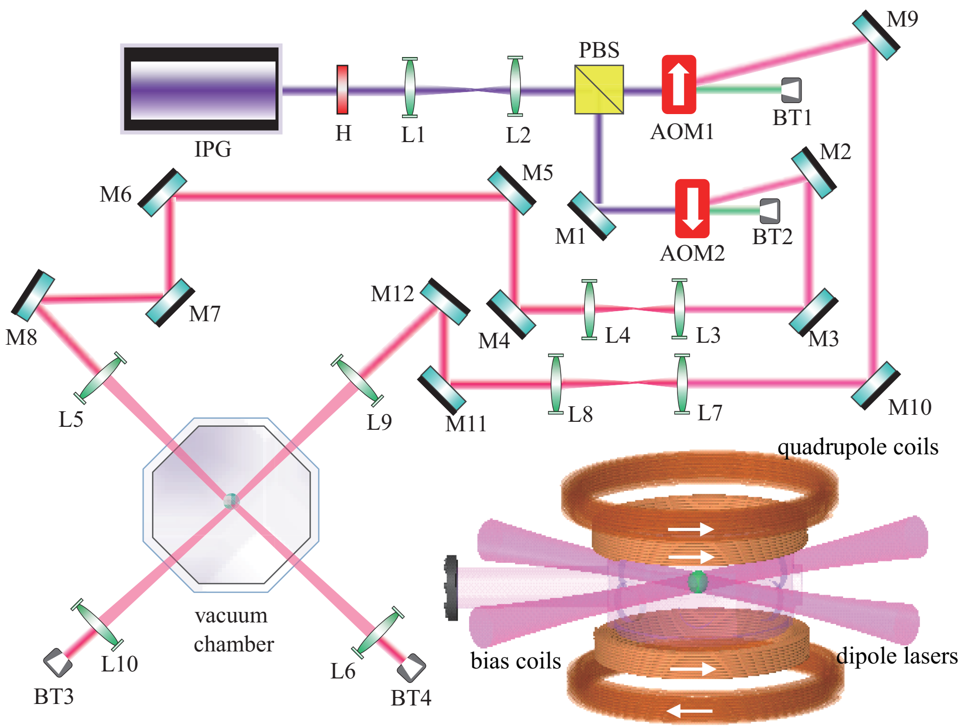

Fig. 3. (color online) Experimental setup for the excessively magnetic levitated loading of a large-volume crossed ODT. Two beams with different frequency shifts, which are obtained by the acousto-optical modulator (AOM), are focused on the center of a vacuum chamber to form a crossed ODT. Two pairs of coils in the Anti–Helmholtz and Helmholtz geometries are used to produce the magnetic field gradient and the bias field in the vertical direction.

To cancel the destructive potential induced by the gravity, the vertical magnetic field gradient is needed to produce the upward magnetic force. At the same time, another uniform bias field is applied in the vertical direction to eliminate the anti-trapping potential along the horizontal direction induced by the magnetic field gradient.[21] In Fig. 3, the magnetic field gradient is produced by the pair of anti-Helmholtz coils used for the MOT, and the Helmholtz coils produce the uniform bias field. In our experiment, the magnetic field gradient is firstly increased to a value that excessively compensates for the atomic gravity, and then is reduced to the value of $B' = 31.3$ G/cm to completely cancel the gravity. The absorption image is taken in the horizontal direction after 3 ms of expansion following the release of the ODT.

4. Experimental results

We measure the dependence of the number of atoms loaded into the crossed ODT on the excessive levitation time t for the three different magnetic field gradients as shown in Fig. 4. The observed variation of the number of atoms with time is consistent with the theoretical variation of the atomic velocity with time as shown in Fig. 2. For $B'_0 = 31$ G/cm in Fig. 4(a), the downward atomic velocity always increases with time because the maximum value of B'_0 does not exceed the critical value B'_G. The continuous heating effect corresponds to the observed decrease in the number of atoms. In comparison, as shown in Figs. 4(b) and 4(c), the number of atoms firstly decreases and then increases with time, and there is a minimum when the downward atomic velocity reaches its maximum at $t_1 = 0.83$ ms (b) and 0.62 ms (c). As the time increases, the number of atoms reaches a maximum when the downward atomic velocity is completely eliminated at $t_2 = 1.9$ ms (b) and 1.3 ms (c). Subsequently, the number of atoms gradually decreases with time $t > t_2$. The locations of the minimum and maximum numbers of atoms in Fig. 4(c) are smaller compared to those in Fig. 4(b).

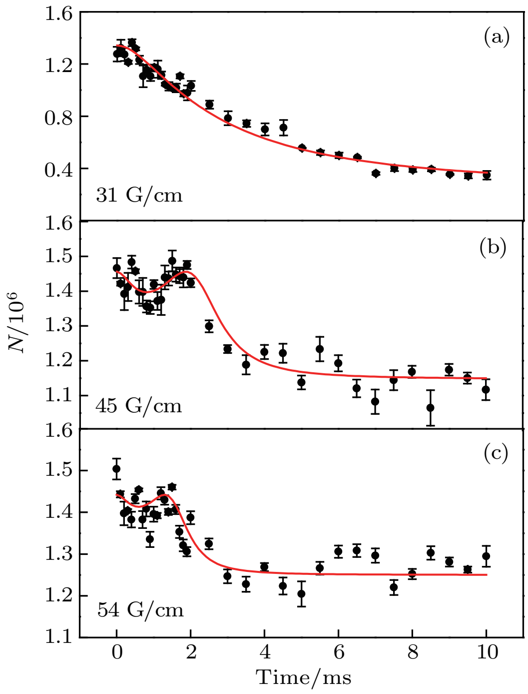

Fig. 4. (color online) The number of atoms loaded into the crossed ODT as a function of the excessive levitation time at the magnetic field gradients of 31 G/cm (a), 45 G/cm (b), and 54 G/cm (c). The red lines are theoretical fitting curves.

According to the dependence of the number of atoms loaded into the ODT on the temperature,[26] the number of the atoms is inversely proportional to the atomic temperature, which is defined as the effective temperature by considering the velocity in Eq. (4). We fit the experimental data by introducing a ratio coefficient, which describes the relation between the temperature and the number of atoms. The theoretical fitting shows reasonable agreement with the experiment.

Figure 5 shows the variation of the number of atoms trapped in the crossed ODT with the magnetic field gradient B'_0 for three excessive levitation times of $t = 1.0$ ms, 2.0 ms, and 4.0 ms. The loading rate reaches a maximum when the atomic velocity reduces to 0 as shown in Fig. 2. The value of B'_0, which corresponds to the maximum number of atoms, decreases with an increasing excessive levitation time. This can be understood by that a relative small B'_0 can eliminate the atomic velocity induced during the magnetically levitated loading process for a long excessive levitation time. A theoretical fitting gives the red lines, where a good agreement between the theory and experiment is observed.

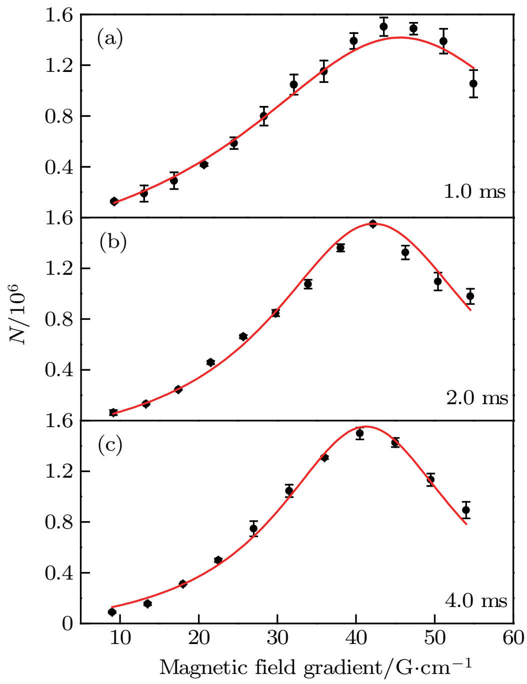

Fig. 5. (color online) Number of atoms loaded into the crossed ODT as a function of magnetic field gradient for the excessive levitation times of 1.0 ms (a), 2.0 ms (b), and 4.0 ms (c). The red lines are theoretical fitting curves.

In Fig. 6, we compare the observed results corresponding to the maximum number of atoms loaded in the crossed ODT with the theoretical curve, which is obtained according to Eq. (4). For the two excessively magnetic field gradients of $B'_0 = 45$ G/cm and 54 G/cm, we can find the two corresponding levitation times $t = 1.9$ ms and 1.3 ms that compensate for the atomic velocity induced in the magnetic levitation process, and load as many precooled atoms as possible into the ODT. Similarly, there are three excessively magnetic field gradients of $B'_0 = 48$ G/cm, 43 G/cm, and 41 G/cm, which can realize an efficient loading for three levitation times $t = 1.0$ ms, 2.0 ms, and 4.0 ms. Experimental results show reasonable agreement with the theoretical calculations. The error bars are obtained by translating the error of the maximum number of atoms in the trap to the levitation time or to the magnetic field gradient.

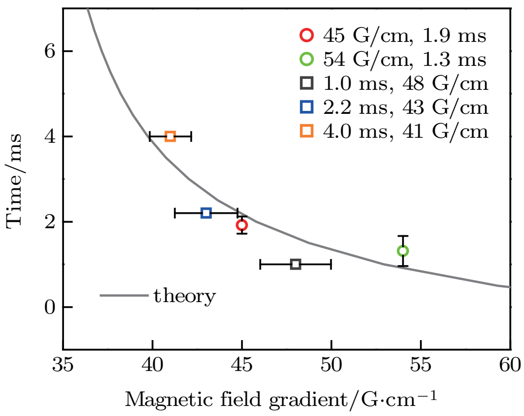

Fig. 6. (color online) Theoretical variation of excessive levitation magnetic fields with the excessive levitation time for an efficient loading of the crossed ODT when the atomic velocity equals zero in Eq. (4). The experimental data (two circles and three squares) are from Figs. 4 and 5, respectively.

5. Conclusion

We have studied the heating effect that occurs during the magnetically levitated loading of ultracold Cs atoms into a large-volume crossed ODT. It is observed that the number of atoms loaded into the ODT is dependent on both the excessive levitation time and the magnetic field gradient. Excessive levitation has been demonstrated to effectively reduce the atomic velocity induced by the non-equilibrium gravito-magnetic force. A brief theoretical model is presented and shows reasonable agreement with the experimental results. The detailed investigation of the excessive levitation could be extended to effectively trapping cold atoms on a chip and to guiding cold atoms.

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