Comparison of different techniques in optical trap for generating picokelvin 3D atom cloud in microgravity

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Abstract

Pursuing ultralow temperature 3D atom gas under microgravity conditions is one of the popular topics in the field of ultracold research. Many groups around the world are using, or are planning to use, delta-kick cooling (DKC) in microgravity. Our group has also proposed a two-stage crossed beam cooling (TSCBC) method that also provides a path to picokelvin temperatures. In this paper, we compare the characteristics of TSCBC and DKC for producing a picokelvin system in microgravity. Using a direct simulation Monte Carlo (DSMC) method, we simulate the cooling process of 87Rb using the two different cooling techniques. Under the same initial conditions, 87Rb can reach 7 pK in 15 s using TSCBC and 75 pK in 5.1 s with DKC. The simulation results show that TSCBC can reach lower temperatures compared with DKC, but needs more time and a more stable laser.

1. Introduction

With the development of space technology, the microgravity environment brings the possibility of new cooling techniques for reducing the temperature of atoms to the picokelvin or even femtokelvin scale [1,2]. Compared with environmental conditions possessing a strong gravitational field, a microgravity environment provides a potential well with less gravity potential, which gives atoms inside the well smaller potential and kinetic energies [3–5]. However, as the temperature decreases, the collision rate between atoms drops. Thus, traditional cooling methods such as simple evaporative cooling take a long time to reach picokelvin temperatures, even in a microgravity environment (i.e., nearly one thousand seconds). Hence, cooling atoms down to lower temperatures under microgravity environment in a short time is still a grave challenge.

In a strong gravitational field, researchers have been able to reach nanokelvin temperatures with evaporative cooling [6,7]. As it is impossible to demonstrate effective cooling to picokelvin temperatures using simple evaporative processes in such an environment, a second stage process in microgravity is necessary for picokelvin cooling. In 2003, A.E. Leanhardt et al. cooled Bose–Einstein condensate (BEC) atoms to 500 picokelvin using an adiabatically decompressed process [4]. In 2013, our group studied the situation in microgravity and proposed a two-stage crossed beam cooling (TSCBC) approach to cool atoms [3]. In this process, we first use a pair of crossed laser beams of micrometer radius and high laser power to form a crossed beam optical trap. By reducing the laser intensity, we perform the evaporative cooling, which cools the atoms in the trap to nanokelvin temperatures in 5 s. Next, we turn on another pair of crossed beams with a millimeter radius and low laser power to form a crossed beam optical trap. By reducing the two beam pairs’ intensity with appropriate parameters, we can achieve an adiabatic decompression process that lowers the atoms to picokelvin temperatures in another 10 s. Another possible technique for the second stage is delta-kick cooling (DKC), which is a cooling method proposed by Hubert Ammann and Nelson Christensen in 1997 [8]. After a free expansion, a kicked pulse is provided to the atoms, which narrows the momentum distribution and provides a quick way to cool the atoms. The 3D case of DKC is studied in [9,10]. In the recent work of Tim Kovachy et al., they even gain 2D Rb gas with 50 pK temperature with DKC [11]. By replacing the adiabatically decompression process with DKC, it is also possible to...
generate an atom system with picokelvin temperatures. Given these different cooling processes, it is still not clear which process is the better choice due to different experimental conditions. The CAL of NASA, the MAIUS and QUANTUS project of Germany and the I.C.E. project of France are all performing or planning to perform DKC on their ultracold system which is under microgravity environment [12–14]. The Chinese Space Station is also planning to demonstrate cooling experiment to picokelvin temperature in 2022 [15]. Therefore, it is vital that we simulate and analyze the physical cooling processes of both techniques to compare their effectiveness.

For both the adiabatic decompression process of TSCBC and the kick process of DKC, the temperature is cooled down to picokelvin levels while maintaining a high phase space density (PSD). Although there is no further increase of PSD, there are still plenty of advantages for such a system in achieving picokelvin temperatures. First, a picokelvin atom system can provide us with an experimental ultracold environment with slower atom velocities and a longer observable life [14]. Secondly, ultralow temperatures are useful for researching precision measurements, quantum information and quantum optics systems [11,16–19]. Finally, such low temperature systems enable us to observe special phenomena that only occur at ultralow energy scales, such as phase transitions [4].

In this paper, we first briefly describe the TSCBC and DKC processes, then simulate the processes using the direct simulation Monte Carlo (DSMC) method. Our simulation results show that the temperature of $^{87}$Rb can be cooled to 7 pK in 15 s using the TSCBC process, and to 70 pK in 5.1 s using DKC. The influence of laser fluctuation and gravity acceleration is also analyzed. Using these results, we summarize the advantages and disadvantages of these two techniques. Finally, we also discuss the sympathetic cooling process for a Bose–Fermi mixture, through which we prove that the two-stage sympathetic cooling and delta-kick sympathetic cooling process for generating a picokelvin ultracold fermion gas is the same as the TSCBC and DKC process used for generating a picokelvin boson gas.

### 2. Simulation of the two different cooling processes

The first step in both the TSCBC and DKC processes is normal evaporative cooling. We assume that this process happens in an optical dipole trap, which is formed by crossing two focused beams in the horizontal plane at a wavelength of 1064 nm with a waist of 60 μm. Similar to the first stage of the TSCBC process for $^{133}$Cs atoms [3], the beam power is ramped down according to

$$P(t) = P_0 \times (1 + t/\tau)^{-\beta}.$$  

where $P_0$ is the initial beam power and $\tau$ and $\beta$ are parameters associated with the ramping curve. This step corresponds to Fig. 1(a), lasts 5 s, and results in atoms at nanokelvin temperatures with quantum degeneracy. We then come to the second step, which is different for the two techniques. For the TSCBC process, the trap is overlapped with a much wider and shallower crossed-beam trap and the narrow beams ramp down according to Eq. (1) using a second pair of $\epsilon'$ and $\beta'$ parameters. After another 10 s, the narrow beams are totally shut down, leaving the wide beams to hold the atoms. In this step of TSCBC, illustrated by Fig. 1(b), an adiabatic decompression process occurs and the temperature decreases by several orders of magnitude while the PSD nearly maintains the same value. For the DKC process, we release the atoms by completely shutting down the trap as soon as the evaporation ends. After a free expansion which lasts for a period $t_2$, a delta kick is performed on the atoms using a short pulse of a laser of time $t_2$ that provides an optical potential. These steps are illustrated by Fig. 1(c) and (d). According to [20], the most important equation in this stage is the impulse provided by the optical trap reducing the atoms’ momentum to nearly zero, i.e.,

$$I_i = m\omega_i^2 v_i t_2 = m\nu^2 \omega_0 t_2 = 1.$$  

Here, $I_i$ is the impulse in the $i$ direction ($i = x, y, z$), $\omega_i$ is the oscillation frequency in the $i$ direction, $m$ is the mass of a single atom, and $v_i$ is the velocity of the atom in the $i$ direction. The approximation we use here is the same as Ref. [20]. This step of the DKC process stretches the positions of the atoms and compresses their momentum in phase space, which also lowers the temperature without changing the PSD. The difference between the TSCBC and DKC procedures is illustrated in Fig. 1. All the optical potential in this simulation is provided by two crossed laser beams like the optical trap in Ref. [21].

In our simulation, the DSMC method described in [22] was employed and the atoms were prepared in the lowest hyperfine
3. Discussion of the two different cooling processes

3.1. Fluctuation of laser power

To insure the above techniques work well under actual experimental conditions, we must consider fluctuations in the laser intensity, as such fluctuations will heat the atoms in the trap. The detailed calculation is stated in the Appendix.

According to the calculation, we can conclude that if we want to keep the atoms temperature stable at the tens of picokelvin scale, we must insure that the power fluctuations of the laser in the TSCBC process are limited to

\[ \frac{\Delta P_T}{P_T} \leq 10^{-4}, \]

while for the DKC process, this value is

\[ \frac{\Delta P_D}{P_D} \leq 10^{-1}, \]

where \( P_T \) is the laser power in the TSCBC process and \( P_D \) is the laser power in the DKC process. From this data, we can conclude that DKC requires less stability of the laser power compared with TSCBC, which is another advantage of the DKC process.

Moreover, for both the two processes, a harmonic trap is assumed. Therefore, the laser intensity profile can also affect the laser frequency. However, as we reach a high PSD in the first step of normal evaporation cooling and maintain this PSD in the second step, the atoms keep locating on the center of the laser beam, where the Gaussian shape fits well.

3.2. Microgravity

During our simulation, we assumed a microgravity environment as it provides a better condition for the two cooling processes. In order to prove this statement, we also simulated the experiments under different gravitational accelerations. Here, we evaluate the best parameters for each gravities and calculate the lowest temperature. The result is shown in Fig. 3. From Fig. 3(a), we can see that the lowest achievable temperature for both TSCBC and DKC decreases as gravitational acceleration decreases. For TSCBC, the reason is that the acceleration in the \( z \) direction (the direction of gravity) gives the atoms more momentum and even enables some of them to escape from the double-crossed beam, as depicted in Fig. 3(b). For DKC, gravitational acceleration in the \( z \) direction makes the atoms move faster during the free expansion, which causes a mismatch with the setting parameters of Eq. (2) during the pulse kick. According to this outcome, we recommend performing both these two cooling techniques under microgravity conditions.

3.3. Cooling an ultracold Fermi gas

With the development of sympathetic cooling [26], ultracold Fermi gases have become another popular topic in ultracold research [27-29]. For this paper, we also simulated TSCBC and DKC...
in conjunction with sympathetic cooling of a mixture of $^87$Rb and $^{40}$K atoms in microgravity. In this simulation, the dipole trap was again formed by crossing two focused beams in the horizontal plane using a wavelength of 1064 nm and a waist of 60 μm. The initial atom numbers and the temperature of $^{40}$K was $5 \times 10^6$ and 200 μK, and for $^{87}$Rb $1.6 \times 10^7$ and 4 μK, respectively. The beam power was ramped down using the parameters $\tau = 0.01$ and $\beta = 0.9$ for Eq. (1) in the first 5 s of evaporative cooling. We achieved $3.3 \times 10^4$ $^{40}$K atoms at 4.98 nK with $8.5 \times 10^4$ $^{87}$Rb atoms at 4.45 nK in this step. For the TSCBC sympathetic cooling process, the result was already calculated in [30], which was $2.9 \times 10^4$ $^{40}$K atoms with a temperature of 51.19 pK in 15 s. For the DKC process, with setting parameters $t_1 = 0.1$ s, $t_2 = 0.001$ s, and $\omega_x = \omega_y = \omega_z = 100$ Hz, we achieved $3.1 \times 10^4$ $^{40}$K atoms with a temperature of 388 pK in 5.101 s. The results of the numerical simulation are shown in Fig. 4, from which we can conclude that TSCBC provides a possible path for Fermi gas to temperatures of $10^{-11}$ K, while DKC offers a quicker method to achieve temperatures of $10^{-10}$ K. Due to this simulation, we can infer that both the TSCBC process and the DKC process are useful for cooling Fermi gases, and their advantages and disadvantages are similar to those when cooling a single boson gas.

4. Comparing the results of the two different processes

The results we achieved using the two different processes are summarized in Table 1. From our simulations, $^{87}$Rb can reach 7 pK in 15 s using the TSCBC process and 75 pK in 5.101 s using the DKC process. The influence of power fluctuations in the lasers was also taken into consideration. According to all of the results, we can conclude that TSCBC provides the possibility of achieving $10^{-12}$ K temperatures in 15 s with a laser stability demand $\Delta P_{L}/P_{L}$ of less than $10^{-4}$, while DKC offers us a quicker way to achieve $10^{-11}$ K temperatures with a laser stability demand $\Delta P_{L}/P_{L}$ of less than $10^{-3}$. There are no obvious differences between these two techniques in terms of the radius and PSD of the resulting atom cloud. Therefore, if the object of the experiment is to reach temperatures of $10^{-12}$ K, TSCBC is the better method. However, if cooling speed is more important or it is not possible to achieve a laser accuracy of $10^{-4}$, it is better to choose DKC as the cooling method. Furthermore, our simulation data shows that the advantages and disadvantages of the sympathetic cooling process of a Bose–Fermi mixture are similar to those of single boson atoms for both cooling methods.

5. Conclusion

We analyzed and simulated two different processes for generating picokelvin temperatures in microgravity: two-stage crossed beam cooling and delta-kick cooling. According to our analysis, TSCBC can reach lower temperatures compared with DKC, but requires more time and a more stable laser. There were no distinct differences in the radius and PSD of the atom clouds between the two methods. With a sympathetic cooling process, the Fermi gas can reach lower temperatures with TSCBC, while DKC takes less time. Moreover, we also analyzed the reasons why a microgravity environment is a better condition for both techniques.

### Table 1

<table>
<thead>
<tr>
<th>Technique</th>
<th>$T_{Rb}$ (pK)</th>
<th>$t_{Rb}$ (s)</th>
<th>$r_{Rb}$ (μm)</th>
<th>$PSD_{Rb}$</th>
<th>$\Delta P/P$</th>
<th>$T_{F}$ (pK)</th>
<th>$t_{F}$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSCBC</td>
<td>7</td>
<td>10</td>
<td>300</td>
<td>3.70</td>
<td>512</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>DKC</td>
<td>75</td>
<td>0.1</td>
<td>100</td>
<td>3.57</td>
<td>388</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>
With the development of modern science, more and more ultracold experiments are able to be conducted under microgravity conditions using techniques such as magnetic levitation, species-specific dipole trap [31], drop towers [14] and in near-Earth orbit on the space station [32]. Because microgravity provides better experimental conditions and simulates the environment of space, it is very important to learn effective techniques for generating ultralow temperatures in a microgravity environment. As these two techniques both provide a possible path to picokelvin temperatures for both bosons and Bose–Fermi mixtures in microgravity, we hope that this comparison will be useful for further exploring the world of ultracold atoms. Moreover, as these two techniques both have their own advantages and disadvantages, it is possible to create a new cooling method by combining these two methods in an appropriate way. Further work could be done on this area.

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Appendix

Here, we perform the calculation of Section 3.1, which shows how the laser fluctuation influence the result of cooling.

Near the center of the crossed dipole trap, the potential can be approximated as

$$U_{dip} \approx \frac{3 \pi c^2 \Gamma}{2 \omega_0^3} \frac{\omega}{\omega_1} \frac{P}{\omega^2}.$$  (5)

in which $P$ is the power of the beams, $w$ is the waist of the beams, $c$ is the speed of light in space, $\Gamma$ is the scattering rate, and $\omega_0$ and $\omega_1$ are the resonance frequency of the atoms and the frequency of the laser beams, respectively. Here, we use the rotating-wave approximation and assume that the two beams of the trap are produced by the same laser. The cooling processes discussed in this paper are assumed to be quasi-static processes. In the ultracold regime, the temperature is a statistical value based on the average kinetic energy $K$ and potential energy $U_{dip}$ of the atoms in three directions, that is

$$3 k_B T = K + U_{dip}.  \quad (6)$$

During the TSCBC process, we can estimate the influence of power fluctuations using the partial differential of $P$ on both sides of Eq. (3), such that

$$3 \frac{\partial T}{\partial P} k_B = \frac{\partial U_{dip}}{\partial P} = -\frac{3 \pi c^2 \Gamma}{2 \omega_0^3} \frac{\omega}{\omega_1} \frac{1}{\omega^2}.$$  (7)

Taking the parameters of $^{87}$Rb atoms ($\Gamma = 2 \pi \times 6.07$ MHz and $\omega_0 = 2 \pi \times 384.23$ THz), the condition of the laser ($w = 60 \times 10^{-6}$ m), and the constants $(k_B = 1.38 \times 10^{-23} \text{ J/K}$ and $c = 3 \times 10^8 \text{ m/s}$ [25]), we can evaluate

$$\frac{\partial T}{\partial P} = 337.5 \left( \frac{pk}{mW} \right) \frac{1}{P}.$$  \quad (8)

For the DQC process, we have

$$\omega^2 \omega_0^2 \omega_1^2 = v - v_0,$$  \quad (9)

where $\omega$ is the oscillation frequency and $v_0$ is the speed of the atom at the beginning of the free expansion. In this equation, we do not ignore the original velocity $v_0$ of the atom because we want to make the estimate as accurate as possible. Using Eqs. (5), (6), and (9), we can estimate the influence of power dithering on the final temperature to be

$$\Delta T = -\frac{2\omega v_0^2 \omega_0^2 \Delta P}{k_B w^2 \omega_0^2 \Delta}.$$  \quad (10)

Using the parameters of $^{87}$Rb atoms, We get

$$\Delta T = -27 \left( \frac{pk}{mW} \right) \frac{1}{P}.$$  \quad (11)

which gives the final expression of the temperature influenced by power fluctuations of the laser. This means that if we want to keep the atoms temperature stable at the tens of picokelvin scale, we must insure that the power fluctuations of the laser in the TSCBC process are limited to

$$\frac{\Delta P_T}{P_T} \leq 10^{-4},$$  \quad (12)

while for the DQC process, this value is

$$\frac{\Delta P_D}{P_D} \leq 10^{-3},$$  \quad (13)

where $P_T$ is the laser power in the TSCBC process and $P_D$ is the laser power in the DQC process.

References


