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Surface-induced evaporative cooling*

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The effects of surface-induced evaporative cooling on an atom chip are investigated. The evolutions of temperature, number and phase-space density of the atom cloud are measured when the atom cloud is brought close to the surface. Rapid decrease of the temperature and number of the atoms is found when the atom-surface distance is < 100 μm. A gain of about a factor of five on the phase-space density is obtained. It is found that the efficiency of the surface-induced evaporative cooling depends on the atom-surface distance and the shape of the evaporative trap. When the atoms are moved very close to the surface, severe heating is observed, which dominates when the holding time is > 8 ms. It is important that the surface-induced evaporative cooling offers novel possibilities for the realization of a continuous condensation, where a spatially varying evaporative cooling is required.

Keywords: atom chip, atom-surface distance, surface-induced evaporative cooling
PACC: 3450D, 3280P

The manipulation of the neutral atoms with the atom chip has opened a new frontier in the field of atom optics.[1,2] The atom chip based on an excellent microfabrication technique could provide a variety of potential geometries and manipulate neutral atoms on the micrometer scales. To date, the trapping,[3−6] guiding[7−11] and transporting[12,13] of the neutral atoms have been realized on the atom chip. Furthermore, the easy creation of the degenerated quantum gases[14−16] on the atom chip provides new possibilities to control coherent matter precisely. However, when the ultracold atoms are brought very close to the surface of the chip, several harmful surface effects, such as corrugated potentials,[17−23] large heating rates[15,17,24] and short trap lifetime,[17,21,25,26] have been found in recent studies. Such effects must be eliminated before the atom chip is applied in practice. On the other hand, the atom-surface interaction could remove the most energetic atoms position-selectively, consequently, decreasing the temperature of remaining atoms. It is so-called surface-induced evaporative cooling,[3,26−28] where the surface effect is constructive.

When the atoms are brought close to a surface, atoms with energy in the direction perpendicular to the surface in excess of the potential at the surface will collide with the surface and consequently escape from the trap. Since the escaped atoms have more energy than the average, the remaining atoms are cooled down after thermalization through elastic collisions. Therefore, the surface-induced evaporative cooling has provided an alternative way of making a Bose-Einstein condensate in place of rf forced evaporative cooling.[29−31] Recently, Bose-Einstein condensation has been created by only using surface-induced evaporative cooling technique,[26] not applying any rf evaporative cooling. Unlike rf forced evaporative cooling, the surface-induced evaporative cooling is one-dimensional. Along this dimension, the surface, as a nearly ideal evaporative knife, can "evaporate" all the hot atoms above a certain energy. As a result, the efficiency of surface-induced evaporative cooling is not lower, compared with that of rf evaporative cooling.[26,27] Furthermore, the surface-induced evaporative cooling is spatial-dependent. By varying the atom-surface distance the efficiency of evaporative cooling can be controlled easily. Accordingly, it is promising to create a continuous Bose-Einstein condensation by the surface-induced evaporative cooling technique.[26,27,32]

In this paper, we demonstrate the surface-induced evaporative cooling in a magnetic microtrap on an

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atom chip. A significant decrease of the temperature and number of the atom clouds is observed when it is moved from the distance of 300 μm to 15 μm from the surface of the chip. At the same time a gain of about a factor of 5 on the phase-space density is obtained. The efficiency of the surface-induced evaporative cooling is found to depend on the atom-surface distance and the shape of the evaporative trap. We also find that in the regime of a large atom-surface distance (> 100 μm), the method does not work. Moreover, in the regime of small atom-surface distance (< 50 μm), the surface-induced cooling is found to be more effective with the shorter distance and the looser evaporative trap. Simultaneously, severe heating is observed, which dominates when the atoms are held very close to the surface in excess of 8 ms.

Our experimental setup has been previously described in Refs.[6] and [11]. The magnetic microtrap is created by sending currents I_Z through a Z-wire in the chip and superposing a homogeneous, external field B_0 which is perpendicular to the central part of the Z-wire. The width w of Z-wire is 100 μm, and the length of the central part of the Z-wire is 2 mm. First we collect about 6×10^6 ^{87}Rb atoms in 5 s from the background vapor using UV mirror-magneto-optical trap (MOT). Next the atom cloud is transferred to the U-MOT, compressed and cooled in optical molasses, and then optical pumped to $5S$, $F = 2$, $m_F = 2$ state. Sequentially, all lasers are shut off and the magnetic microtrap which is called loading trap is switched on with $I_z = 2$ A and $B_0 = 13.2 \times 10^{-4}$ T (1 Gs = 10^{-4} T). By the end of this sequence, the loading trap contains about 1.5×10^6 atoms which are located at 300 μm from the surface of the chip.

After holding the atom cloud in the loading trap 500 ms for thermalization, we move the atom cloud adiabatically to the evaporative trap by changing the current I_Z of the Z-wire and the bias field B_0 simultaneously. The relations between the current I_Z, the bias field B_0 and the distance d are shown in Fig.1(a). When the distance d of the center of the evaporative trap from the surface of the chip is > 100 μm, the current of Z-wire I_Z varies linearly with the distance d, which is given by $I_Z = 5000d + 0.5$, and the bias field B_0 varies with the distance d and the current I_Z correspondingly[33] and can be expressed as

$$B_0 = \frac{\mu I_Z}{\pi w}\left(\frac{\pi}{2} - \arctan\frac{2d}{w}\right). \tag{1}$$

At 100 μm, the current I_Z is 1 A, and the bias field B_0 is 18.5×10^{-4} T, the gradient of the trap is 1.6×10^{-1} T/cm, respectively. When the distance is < 100 μm, the gradient of the trap is maintained at 1.6×10^{-1} T/cm by varying the currents of the Z-wire I_Z and the bias field B_0 with the distance d simultaneously. The current I_Z is given by

$$I_Z = \frac{d^2 + (w/2)^2}{(100 \times 10^{-6})^2 + (w/2)^2}. \tag{2}$$

The corresponding bias field B_0 is given by Eq.(1). To ensure the gradient of the trap constant, the movement of the atom cloud close to the surface is divided into six steps: 300 μm $\rightarrow$ 200 μm $\rightarrow$ 100 μm $\rightarrow$ 50 μm $\rightarrow$ 35 μm $\rightarrow$ 20 μm $\rightarrow$ 0 μm and in each segment the current I_Z and the bias field B_0 vary nearly linearly with the distance d from the surface. During the movement the magnetic field at the bottom of the trap is set to 2×10^{-4} T. In this way, Majorana spin flips can be avoided and the shape of the magnetic trap does not change during the movement. When the atom cloud is moved to the desired distance from the surface, it will be held 5 ms in the evaporative trap to interact with the surface of the chip. Those atoms with energy in the direction perpendicular to the surface in excess of the potential at the surface are removed from the trap by colliding with the surface. In the interval of 100 ms, the remaining atoms are moved adiabatically back to the imaging trap with $I_Z = 2$ A and $B_0 = 9.85 \times 10^{-4}$ T which is located at 400 μm from the surface of the chip. Because the atom cloud is far away from the surface, the imaging quality is improved dramatically, the temperature and number of the atom cloud can be measured accurately. Alternatively, the adiabatic decompression maintains the phase-space density. It is then followed by holding the atom cloud another 500 ms for rethermalization. At last the temperature and number of the atom cloud are detected by absorption imaging on the $F = 2 \rightarrow F' = 3$ transition. The scheme of temporal sequence in the experiment is described in Fig.1(b). When the distance of the center of evaporative trap from the surface is ≥ 100 μm, the atoms are moved to the desired distance in 100 ms. When the distance is < 100 μm, the atoms are moved from 300 μm to 100 μm in 100 ms, from 100 μm to the desired distance in another 100 ms.

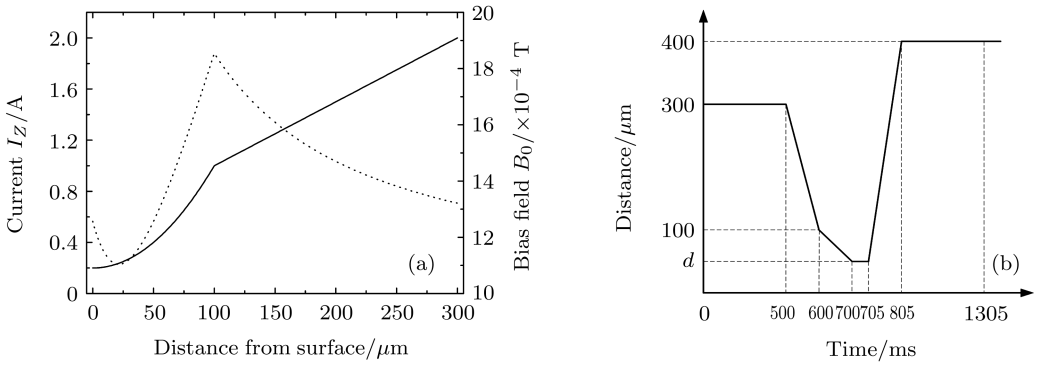


Fig.1. (a) The current I_Z and bias filed B_0 versus the distance of the center of the evaporative trap from the surface. When the distance is ≥ 100 μm, the current I_Z varies linearly with distance. When the distance is < 100 μm, the current I_Z and bias field B_0 vary with the distance simultaneously to ensure the gradient of the trap constant. (b) The scheme of temporal sequence in our experiment. When the distance is ≥ 100 μm, the atoms are moved to the desired distance in 100 ms. When the distance is < 100 μm, the atoms are moved from 300 μm to 100 μm in 100 ms, from 100 μm to the desired distance in another 100 ms.

Figure 2 shows the dependence of the temperature, number and phase-space density of the atom cloud remaining in the imaging trap on the atom-surface distance. When the distance d is ≥ 100 μm, the temperature and number of the atom cloud as well as phase-space density, do not change with the distance. In other words, when the atom is far away from the surface, the surface-induced evaporative cooling does not work. When the distance is < 100 μm, the temperature and the number decrease rapidly with the distance. At 20 μm, the temperature drops down to 48 μK, nearly half of the temperature at 300 μm and at the same time the atoms loss is more than 60%. Moreover, the phase-space density increases by more than a factor of 2. Particularly, it must be pointed out that the cooling of the atoms during the movement does not arise from the surface-induced evaporative cooling only. From the evolution of the trap depth during the movement, shown in Fig.2(d), we can see that during the movement to the surface the atoms in the evaporative trap experience two different cooling processes successively, which work at different atom-surface distances. When the trap center-surface distance is > 50 μm, the trap depth is determined by the bias field B_0, which decreases with the decreasing distance from the surface; in other words the trap depth decreases gradually. The atoms with energy in excess of the trap depth will escape from the trap in the direction far away from the surface. Therefore, the temperature of the remaining atoms will decrease after thermalization. The evaporation of the atoms is done by lowering the height of the trapping potential in this process. However, when the distance is < 50 μm, the trap depth is determined by the height of the potential barrier at the surface. The most energetic atoms will collide with the surface, and then escape from the trap. The remaining atoms are cooled down after thermalization. The trap depth becomes further shallow with decreasing distance. The atoms with high energy continue to collide with the surface, and then the cooling of the atoms goes on. This is surface-induced evaporative cooling where the surface acts as a sharp evaporative knife. The continuous decreases of the trap depth with the atom-surface distance in the two cooling processes, are similar to the sweep of rf frequency in the rf-forced evaporative cooling. Compared with the first cooling process, surface-induced evaporative cooling is more effective and works in the region more close to the surface.

To further investigate the effect of surface-induced evaporative cooling, we study the evolution of the temperature, the number and the phase-space density in various shapes of the evaporative trap. Experimentally, we fix the position of the center of evaporative trap, vary the gradient of the evaporative trap, and then measure the temperature, number and phase-space density of the atom cloud remaining in the imaging trap. Three series of measurements are shown in Fig.3, in which three different values of the gradient of the evaporative trap are used: 1.120×10^{-1} T/cm, 1.600×10^{-1} T/cm and 3.360×10^{-1} T/cm, respectively. From Fig.3 it can be seen that under the three

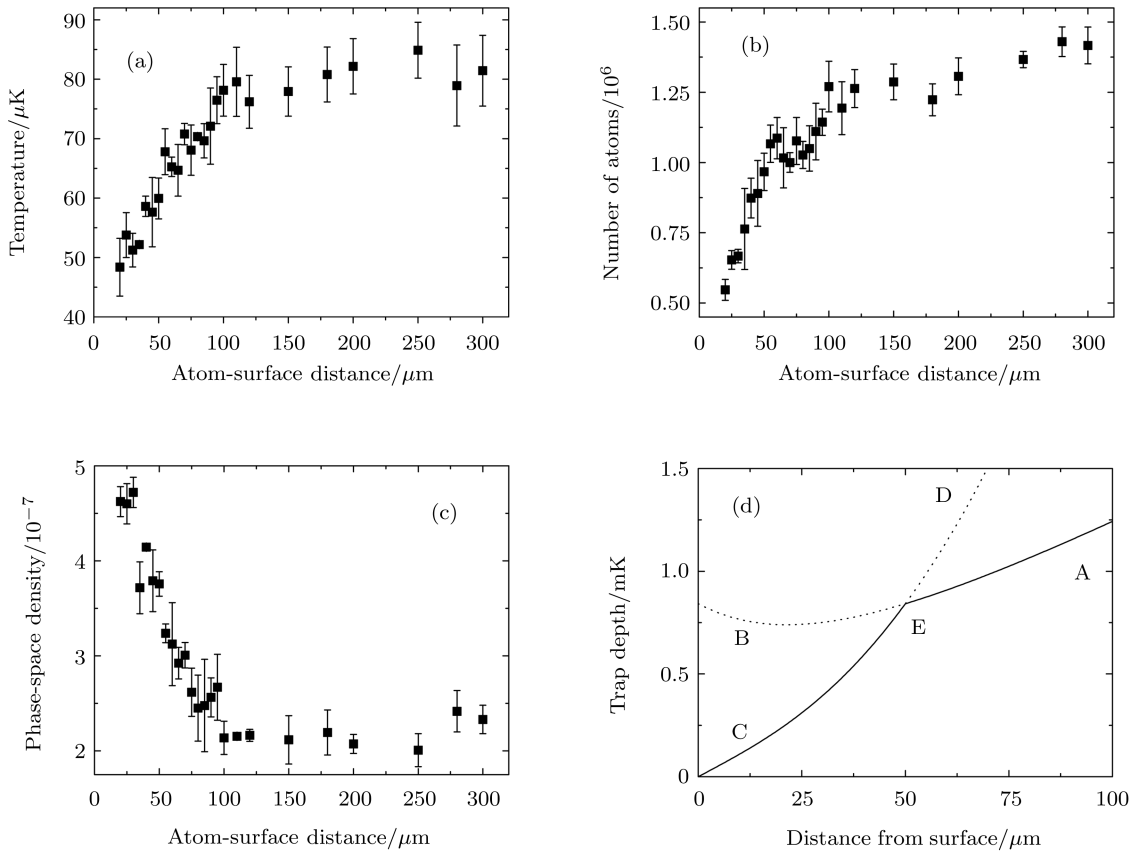


Fig.2. The surface-induced evaporative cooling, which depends on the atom-surface distance. When the distance is ≥ 100 μm, the temperature (a), number (b) and phase-space density (c) are all kept nearly constant during the movement. When the distance is < 100 μm, the temperature as well as the number drops down rapidly. The phase-space density gains more than a factor of 2 when the atoms are moved to the distance of 20 μm. (d) The evolution of the trap depth (curve AEC) during the movement of the atoms from 100 μm to the surface. The flexion point E corresponds to the distance 50 μm from the surface. The trap depth decreases continuously with the distance from the surface. Curves AB and CD represent the bias field B_0 and the field on the surface of the chip, respectively.

conditions, both the temperature and number decrease with the distance; moreover, at a given distance from the surface, the looser the evaporative trap, the lower the temperature of the remaining atoms, and the smaller the atom number and the larger the phase-space density. It indicates that the surface-induced evaporative cooling is more effective in the looser evaporative trap. It is easily understood: suppose that the initial temperatures in evaporative trap be the same at the three conditions. The atom cloud in the looser evaporative trap has a larger in-trap rms size, that is to say, the trajectories of the atoms with high energy in looser evaporative trap are larger than in the tighter trap. When the center of evaporative trap is moved close to the surface, the atoms with high energy in the looser evaporative trap have a higher probability to collide with the surface of the chip than that in the tighter evaporative trap. Thus much more atoms with high energy can escape from the looser evaporative trap. Consequently, the temperature of the remaining atoms is lower after thermalization. On the other hand, as shown in Fig.3(d), the trap depth with the gradient of 1.120×10^{-1} T/cm is shallower than that with the other two gradients. Therefore, the atoms with high energy can collide with the surface more easily in the trap with the gradient of 1.120×10^{-1} T/cm.

In addition, we hold the atom cloud at a distance of 30 μm from the surface for different holding times, and compare the temperature and the phase-space density of the remaining atoms. It is expected that the atoms are cooled down and phase-space density increases persistently with the holding time. The experimental result is shown in Fig.4. In contrast to the expected cooling, we find that when the holding time is > 8 ms, the temperature starts to increase as the

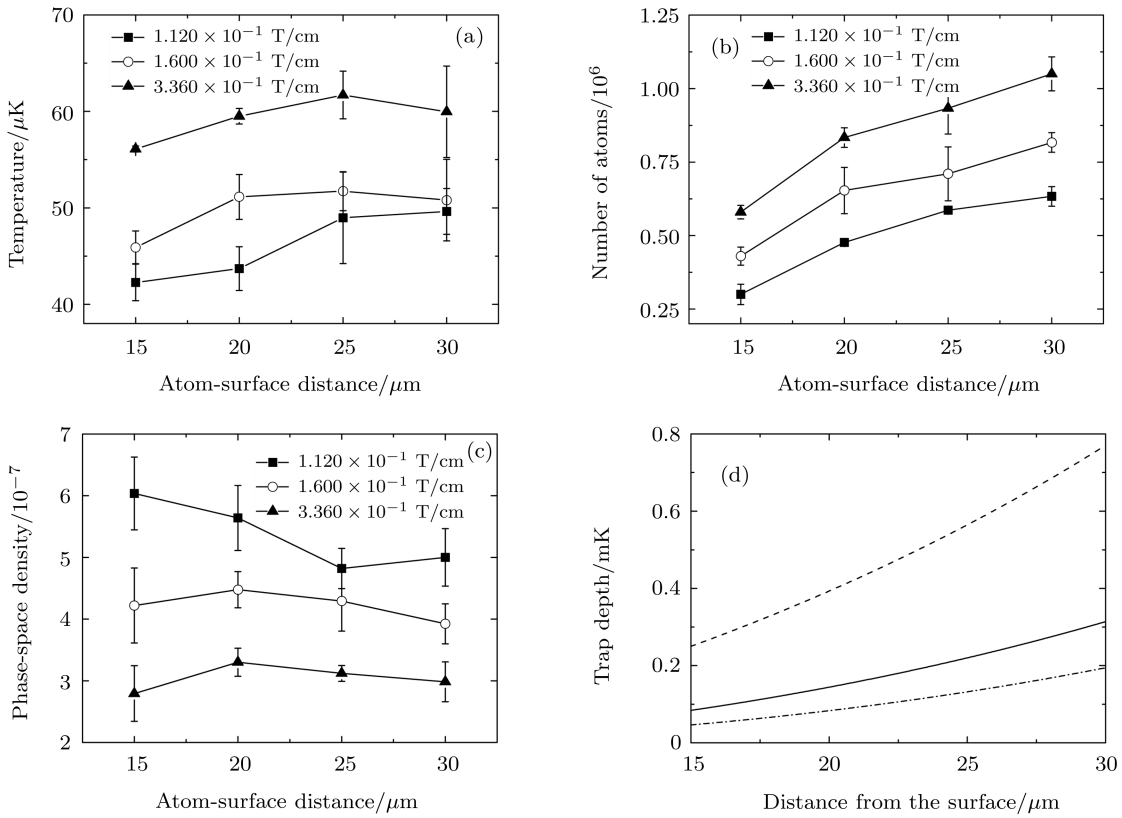


Fig.3. The evolution of the temperature (a), number (b) and phase-space density (c) in three different shapes of evaporative trap. The efficiency of the surface-induced evaporative cooling is shown to depend on the shape of the trap. The evaporative cooling in the trap with 1.120×10^{-1} T/cm is most effective. (d) The evolutions of the trap depth under the three conditions: 1.120×10^{-1} T/cm (dot-dashed lines), 1.600×10^{-1} T/cm (solid lines), 3.360×10^{-1} T/cm (dashed lines). All of the trap depth decrease with the distance. At a given distance, the trap depth with 1.120×10^{-1} T/cm is the smallest.

holding time increases, at the same time the phase-space density starts to decrease. The experimental results suggest that the heating exists in the process of the evaporative cooling. In the beginning, the evaporative cooling effect dominates and the temperature of the remaining atoms decreases. At 8 ms, the two effects counteract each other and as a result, both the temperature and phase-space density reach equilibrium. When the holding time is > 8 ms, the heating effect dominates, thus, the temperature increases while the phase-space density decreases. This heating may be induced due to the thermally excited currents in metallic substrate,[21] technical noise arising from the fluctuations in the currents[17,19] used in the experiment, which needs a further investigation.

Finally, we optimize the process of the surface-induced evaporative cooling to obtain cold atom cloud with lower temperature and larger phase-space density. Here we maintain the gradient of the trap 1.000×10^{-1} T/cm when the distance of the atom cloud from the surface is < 100 μm, and optimize carefully the trajectory of the movement of the atom cloud to the surface and the time that every step requires. The optimized trajectory of the movement is displayed in Fig.5(a). After the optimized surface-induced evaporative cooling, the remaining atoms are cooled down to about 35 μK and the phase-space density reaches 1×10^{-6}, which is about 5 times as large as that at 300 μm. Even though the phase-space density of the atom cloud increases to a great extent, it is still far from realization of the Bose–Einstein condensation. The main reasons that restrict the further increase of the phase-space density are various: first, the lifetime of the atom cloud in our experiment is a critical matter. The lifetime is just about 4 s when the atom cloud is far away from the surface. The lifetime

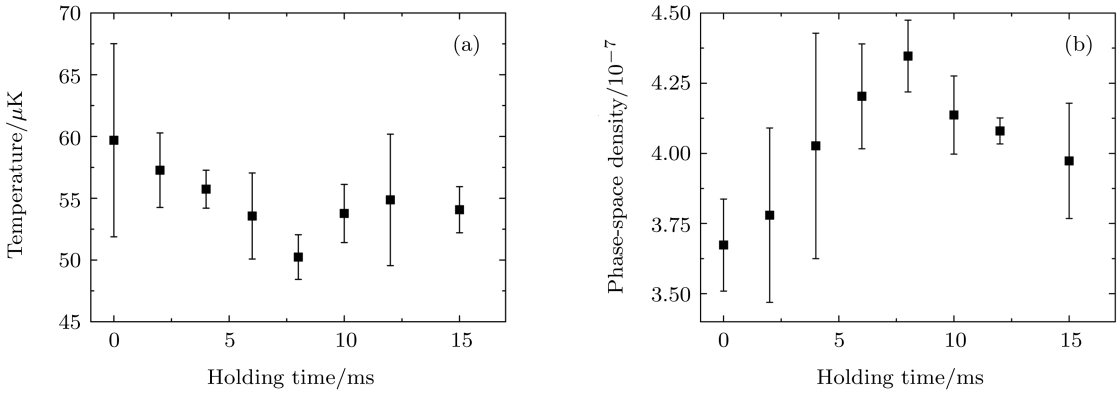


Fig.4. The evolution of the temperature (a) and phase-space density (b) for different holding time when the atoms are held at 30 μm.

decreases roughly linearly with the distance from the surface. At 100 μm, the lifetime drops down to less than 2 s, which is about 500 ms at 20 μm. Therefore, in our experiment it is impossible to move the atom cloud to the surface in tens of seconds, as in Ref.[26]. Only a small fraction of atoms with high energy can collide with the surface and escape from the trap, a great majority of atoms with high energy have no choice to collide with the surface and thus contribute nothing to the surface-induced evaporative cooling. Moreover, the short lifetime of the atom cloud means high background gas collisions ("bad collisions"), which leads to the loss of atoms, and then destroy the evaporative cooling. Second, the severe heating counteracts the effect of surface-induced evaporative cooling when the atom cloud is moved very close to the surface. The heating may be induced due to the thermal noise and the technical noise. The extreme current stabilization may be necessary. Third, the number of the atom cloud is so small that the elastic collisions ("good collisions") in the evaporative trap, which are necessary for evaporative cooling, is few. The few elastic collisions and many bad collisions result in a small ratio of good to bad collisions, which is not up to the requirement of the run-away evaporative cooling.[34]

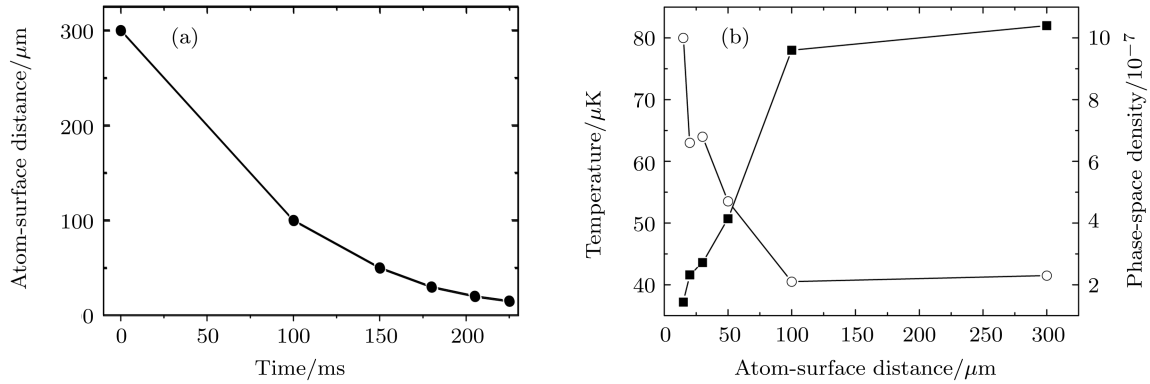


Fig.5. Optimization of the surface-induced evaporative cooling. (a) The optimized trajectory of the movement of the atom cloud. The movement is divided into 5 steps. The gradient of the trap maintains 1.120×10^{-1} T/cm when the atom-surface distance is < 100 μm. (b) The evolution of the temperature and phase-space density of the atoms. At 15 μm, the atoms are cooled down to 35 μK, and gain a factor of about 5 on phase-space density.

In conclusion, we have studied the evolutions of the temperature, number and phase-space density of the atoms when they are moved close to the surface of the chip. The surface-induced evaporative cooling effect is observed. When the atom cloud is moved to the distance of 15 μm from the surface, the phase-space density gains about a factor of 5. Furthermore, the dependence of the surface-induced evaporative cooling on the atom-surface distance and the shape of the evaporative trap is investigated. The evaporative cooling is more effective with smaller atom-surface distance and smaller gradient of the evaporative trap. When the atom cloud is moved very close to the surface, severe heating is also observed, which dominates when the holding time is > 8 ms. Consequently, the atoms are heated up and the phase-space density of atoms begins to decrease. Particulary,

this surface-induced evaporative cooling technique may be useful in the situation where a spatial-dependent cooling is required, such as the continuous condensation schemes.

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