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Shaking-induced cooling of cold atoms in a magnetic trap

M. Kumakura, Y. Shirahata, Y. Takasu, Y. Takahashi, and T. Yabuzaki
Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan

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By shaking a magnetic trap spatially, trapped cold Rb atoms are either heated or further cooled, depending on the shaking frequency. The atom temperature as a function of shaking frequency exhibits a dispersion-shaped resonance, which is caused by frequency selective energy absorption due to the anharmonicity of the trap potential. Selective heating of high-energy atoms enhances their loss, which can result in cooling rather than heating of a trapped atomic cloud.

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Laser-cooled atomic gases and their quantum degenerate states are fascinating systems for studying classical and/or quantum nonequilibrium dynamics due to their high controllability, good optical accessibility, and wide applicability [1]. So far, novel research on nonlinear classical and/or quantum system such as, for example, quantum chaos in kicked atoms [2], chaos-assisted tunneling [3], and atom-optics billiards [4] has been done.

As seen in these studies, nonlinear dynamics of cold atoms is expected to reveal a rich variety of physical phenomena. In this paper, as an example of such an investigation, we will report on the thermal effect for a confined atomic cloud caused by spatially shaking the magnetic trap. It could be expected that the shaking would result in only heating of the trapped atoms because they are subjected to the forced oscillation introduced by the shaken trap potential. We have, however, observed unexpectedly that the shaking induces not only heating but also cooling of the trapped atomic cloud.

The experimental procedure is as follows. By means of a double magneto-optical trap (MOT) system [5], approximately 1×10^9 ^{87}Rb atoms were, at first, collected and laser cooled in a high-vacuum glass chamber. The background pressure was about 7×10^{-9} Pa. The laser-cooling transition for the MOT is $5^2S_{1/2}(F=2)\rightarrow5^2P_{3/2}(F=3)$ ($\lambda=780$ nm), and the $5^2S_{1/2}(F=1)\rightarrow5^2P_{3/2}(F=2)$ transition is also used for repumping the atomic population escaping from the cooling cycle. Next, after turning off the lasers and the magnetic field for the MOT, the atoms were cooled further with the polarization gradient cooling method [6] by using the cooling transition. After these optical cooling processes, the cold atoms were optically pumped into the magnetic sublevel $F=2, m_F=2$ by using the $5^2S_{1/2}(F=2)\rightarrow5^2P_{3/2}(F=2)$ transition under a small bias magnetic field of about 5 G, and were transferred into the magnetic trap.

The magnetic trap consisted of 12 coils placed in the cloverleaf configuration [7] (Fig. 1). The axial magnetic field (along the z direction in Fig. 1) was approximately harmonic and its gradient B_z'' was about 140 G/cm^2. On the other hand, the radial magnetic field (approximately a quadrupole field) for the confinement was applied with the gradient coils. The radial field gradient B_r' was almost constant (about 180 G/cm) and the radial field was nearly zero at the center of the trap. The magnetic-field strength at the trap center was about 1.2 G, which corresponded to the minimum magnetic-field strength B_0 of the trap. The oscillation frequencies of a trapped atom along the radial and axial directions at the trap center (denoted by ω_r and ω_a, respectively) were about $2\pi\times210$ Hz and $2\pi\times16$ Hz, respectively. The cutoff energy for this trap was about 4.8 mK, which was caused by a magnetic field generated at a radio frequency (RF) of 50 MHz.

After the loading into the magnetic trap, the atom cloud was thermalized for 1 s. The number of trapped atoms was typically 2×10^8 and the temperature was about 1 mK. The diameter of the atom cloud was about 2 mm along the radial direction, and the length was about 5 mm along the axial direction. The lifetime was about 90 s, and without shaking the magnetic trap the temperature was almost constant for more than 5 s.

We shook sinusoidally the magnetic trap for 2 s along the radial direction by varying sinusoidally the vertical bias magnetic field (the shaking frequency is denoted by ν_s hereafter). This shaking induces a forced oscillation to the motion of the trapped atoms. The amplitude of the trap shaking, hereafter denoted by Δ, was typically 0.5 mm. After shaking the trap, the atomic cloud was thermalized for 3 s and was

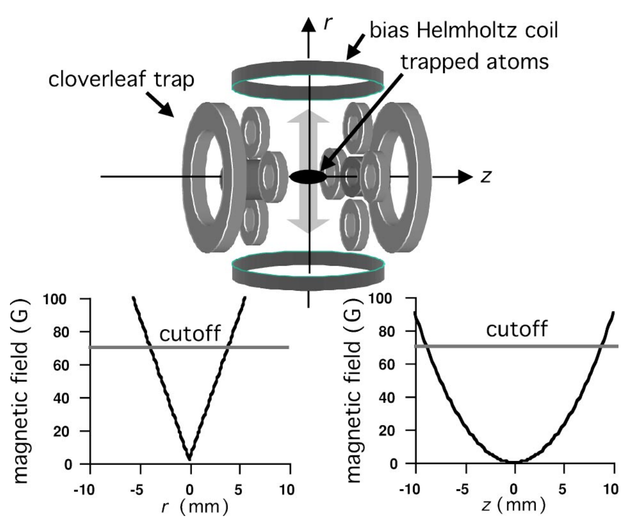

FIG. 1. Experimental setup for the magnetic trap (upper figure) and the magnetic-field strengths along the radial (lower left) and axial (lower right) directions ($|B_r|$ and $|B_z|$, respectively). The horizontal lines in the lower two figures indicate the cutoff energy of the trap, and only atoms colder than this cutoff are confined in the trap.

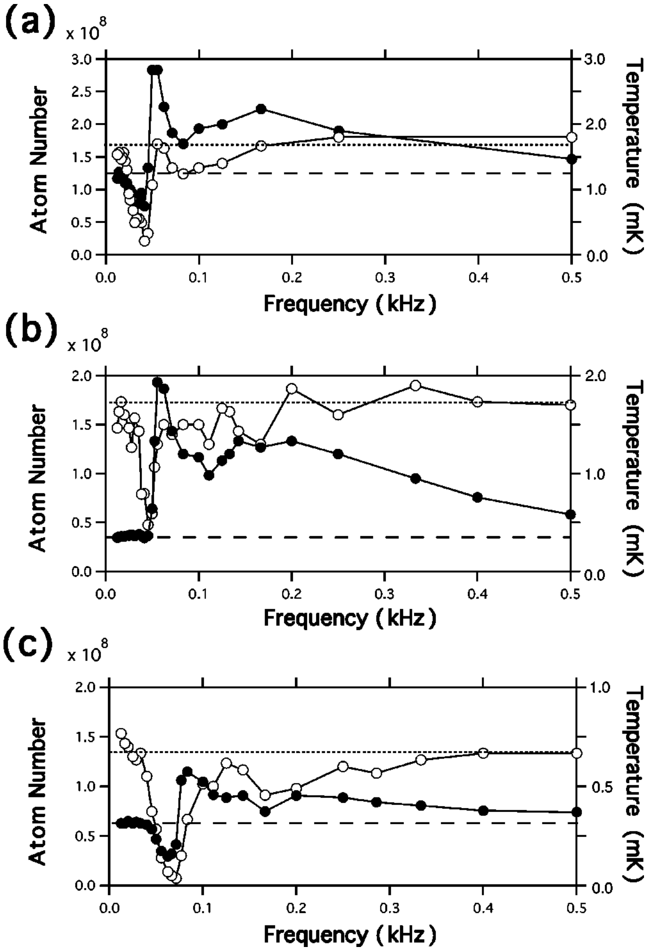

FIG. 2. Temperature (solid circles) and atom number (open circles) as functions of the shaking frequency for the initial temperatures of 1.3 mK (a) and 0.36 mK (b),(c). The cutoff RF frequency is about 50 MHz (corresponding to 4.8 mK) for (a) and (b), and is 20 MHz (2.0 mK) for (c). The minimum magnetic field at the trap center is 1.2 G. Dotted and dashed lines in each figure show the atom number and temperature without shaking, respectively.

released from the trap by turning off all magnetic fields. The temperature and atom number of the atom cloud were measured after a time of flight of 5 ms by the absorption imaging method.

The temperature and atom number as functions of the shaking frequency ν_s are shown in Fig. 2(a). As one might expect, at ν_s larger than 40 Hz the atom cloud in the trap was heated by the shaking. However, the ν_s dependence of the temperature shows a resonant behavior with a dispersion shape. At ν_s less than 40 Hz the cloud was cooled, and the temperature became a minimum at 35 Hz. This resonance frequency is much less than $\omega_r/2\pi$ and is much larger than $\omega_a/2\pi$. At ν_s around 80 Hz, i.e., at the second harmonic of 40 Hz, the depression of the heating is also seen. The atom number decreased at about 40 Hz and 80 Hz corresponding to the resonance frequencies seen in the temperature [8,9]. We calculated the phase-space density at the trap center, denoted by ρ hereafter, from the temperature and atom number, and found that ρ was increased by a factor of about 2 at 30 Hz in the above case.

When the initial temperature was decreased by applying the RF magnetic field for evaporative cooling [10] before shaking, the ν_s dependence of the temperature after shaking changed dramatically. At the initial temperature of 0.36 mK the atom cloud was only heated and no cooling effect could be observed over the whole range of ν_s [Fig. 2(b)]. As ν_s was increased, the temperature rose rapidly at about 60 Hz and this heating effect continued in the range of higher ν_s. The dispersion-shaped resonance observed at the initial temperature of 1.3 mK [Fig. 2(a)] was not seen, but the atom number decreased significantly at about 45 Hz. In this case the value of ρ was only decreased by shaking.

Nevertheless, as seen in Fig. 2(c), even at this initial temperature of 0.36 mK, the cooling effect was reproduced when the trap cutoff energy was decreased from 4.8 mK to 2 mK by applying a RF magnetic field with a frequency of 20 MHz. The ν_s dependence of the temperature shows the dispersion-shaped resonance again, and the resonance frequency was about 70 Hz, which was approximately two times larger than that in the case of the previous initial temperature of 1.3 mK. The atom number also decreased resonantly at this frequency and at the second harmonic.

To make clear the role of the cutoff energy, we show the absorption images after shaking for these two cutoff energies in Fig. 3, which were obtained at the same initial temperature (0.36 mK) and at the same shaking frequency (53 Hz). The upper right image shows the case that the cutoff energy is 4.8 mK (the RF field frequency of about 50 MHz). In this case we see that the off-centered atoms having high initial energies were selectively heated and diverged in the trap by shaking. The cutoff energy in this case is too high for heated atoms to escape from the trap. The atoms with low initial energies remained cold in the vicinity of the trap center, in spite of shaking. On the other hand, when the cutoff energy was decreased to 2.0 mK (the cutoff RF field frequency of about 20 MHz), the atoms heated by shaking escaped evaporatively from the trap as seen in the lower right image of Fig. 3. These experimental results indicate that the shaking of the trap potential excites confined atoms selectively in energy and that the observed cooling effect is due to the evaporation of a hot part of excited atoms.

To understand the cause of this energy selective excitation further, we numerically simulated the classical motion of an atom, and estimated the oscillation amplitude as a function of ν_s. In this simulation, we only considered one-dimensional motion along the radial direction from the trap center, ignoring the cross-dimensional anharmonic mixing [11]. We ignored also atomic collisions and hence thermalization or evaporation processes in the actual atom cloud.

The trap magnetic field $B(x)$ along the radial axis (the x axis) can be expressed as $B=(B_r'x,0,B_0-B_z''x^2/4)$, and the trap potential energy $U(x)$ is approximately expressed as $U(x)=\mu[B_0^2+(B_r'^2-B_z''B_0/2)x^2]^{1/2}$, where μ is the magnetic dipole moment. In this calculation, field intensity and gradients were chosen to be $B_0=1.2$ G, $B_r'=180$ G/cm, and $B_z''=140$ G/cm^2, which were the same as in the present experiment. In this condition, the trap potential $U(x)$ is well approximated by the linear function $\mu B_r'|x|$ except around the trap center.

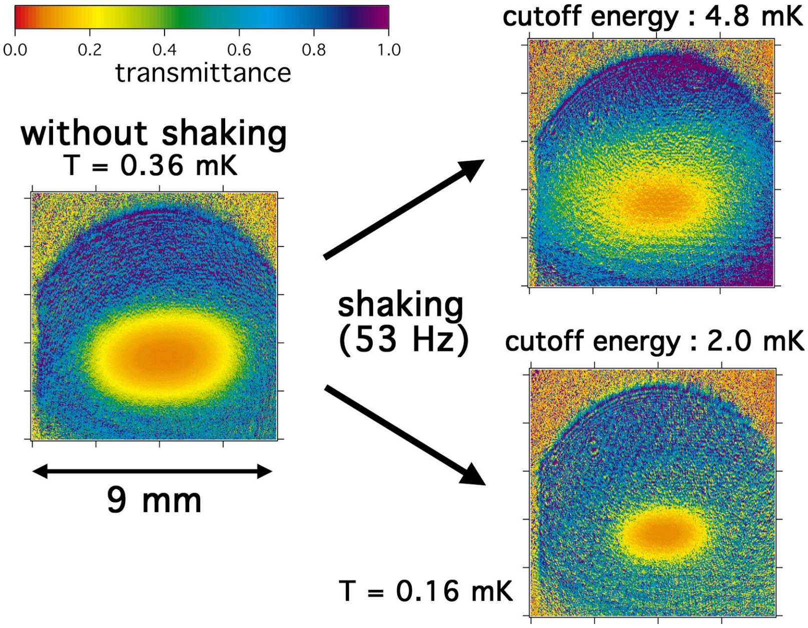

FIG. 3. (Color) Absorption images of the cold Rb atom cloud after shaking the magnetic trap. The right two images show the ones after shaking; the upper and lower ones were observed under the trap cutoff energies of 4.8 mK and 2 mK, respectively. The left image indicates the one without shaking, and the initial temperature was 0.36 mK in all cases. All these images were measured at 5 ms after the release from the magnetic trap.

In the absence of shaking, the atomic motion is determined from the equation of motion $d^2q/dt^2 + (1/m)dU(q)/dq = 0$, where q is the atom position from the trap center and m is the atomic mass. The time evolution of q was calculated by numerically solving this differential equation, with the initial condition that the velocity $v = 0$ at the position $q(0)$ $(= q_0$: the initial oscillation amplitude), in order to know the oscillation frequency $\omega(q_0)$ of the trapped atom. The q_0 dependence of $\omega(q_0)/2\pi$ thus obtained is shown in the inset of Fig. 4. The frequency $\omega(0)/2\pi$ at the trap center is in accord with the value of $\omega_r/2\pi$, and with increasing q_0 the frequency $\omega(q_0)/2\pi$ decreases rapidly. This q_0 dependence is understood as a result of the anharmonicity of the trap potential and is determined mainly from the linear part of the trap potential (see the dotted line in the inset in Fig. 4) [12].

The atom motion in a frame moving with the shaken trap was determined from the equation of motion $d^2q/dt^2 - \Delta\omega_s^2\sin(\omega_s t + \theta) + (1/m)dU(q)/dq = 0$, where the angular frequency $\omega_s = 2\pi\nu_s$ and θ is the relative phase of the shaking. The second term represents the seeming acceleration due to the trap shaking, which induces the forced oscillation in the atom motion. It is expected that the shaking energy is most effectively absorbed by the atom with the frequency $\omega(q_0)$ resonant to ω_s. To confirm this, we calculated the time evolution of q for various values of q_0 and ω_s by numerically solving the equation of motion under the initial condition that $v = 0$ and $q(0) = q_0$. The obtained $q(t)$ oscillated with varying amplitude and frequency, and its maximum amplitude $\max(|q(t)|)$ strongly depended on q_0 and ω_s. The maximum amplitude also depended on θ slightly, and was averaged over $0 \leqslant \theta < 2\pi$. In Fig. 4 we show the ratio of the average maximum amplitude to the initial amplitude, which will be called amplification factor hereafter.

As seen in Fig. 4, the near resonant atom absorbs the energy of the shaking, but the most efficient absorption is caused by the atom with a slightly higher oscillation frequency $\omega(q_0)$ (that is, by the atom with a smaller q_0). For example, at the shaking frequency ν_s of 25 Hz the oscillation amplitude q_0 of the resonant atom is calculated to be about 5 mm, but the most efficient absorption is caused by the atom with the amplitude q_0 of about 3.3 mm. This may be understood by considering the increase of the amplitude during heating; the atom initially resonant for the energy absorption becomes off-resonant due to the increase of the oscillation amplitude, while the atom with a smaller q_0 becomes closer to the resonance and absorbs more energy. Such a positive feedback causes an abrupt change in the amplification factor in the low q_0 side, and results in the asymmetric q_0 dependence of the amplification factor.

In spite of a very simplified model, our theoretical result described above explains roughly the experimental result shown in Fig. 3. As seen in the lower right image in Fig. 3, showing the case that $\nu_s = 53$ Hz, the atom with a radial amplitude less than about 1 mm remains in the trap, which agrees well with the theoretical value of q_0 at which the atom does not efficiently absorb the shaking energy in the case that $\nu_s \sim 40$ Hz. From this fact, although the experimental condition is slightly different from the theoretical one, we can confirm again that the radial anharmonicity of the magnetic trap is essential for the selective excitation and cooling observed in the present experiment.

Similar cooling was also observed by Poli *et al.* [11], when the atoms in an optical trap were subjected to parametric excitation by modulating the intensity of a trap laser beam. In their case the atom excitation was realized by the modulation of the trap shape and depth, which is in good contrast with the present work where the atom is excited only by the spatial shaking of the magnetic trap without changing the trap shape and depth. In both cases, the cooling mechanism is due to the energy selective excitation and evaporation of heated atoms. However, an optical trap is generally much shallower and smaller, so that it is difficult to observe directly the processes of excitation and evaporation

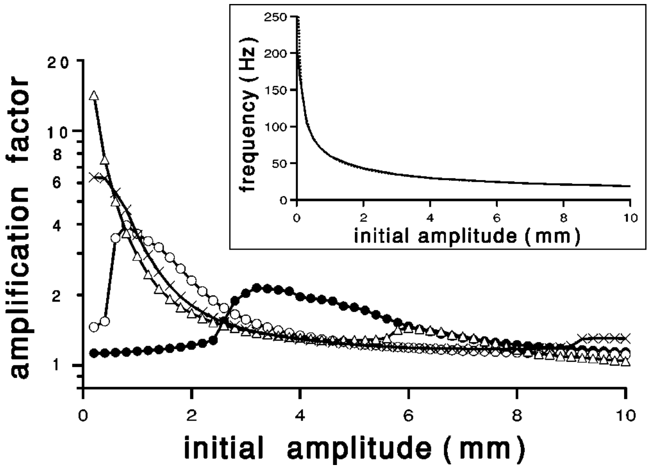

FIG. 4. Theoretical amplification factor, defined by the ratio of the oscillation amplitudes of confined atoms after and before shaking. The points ●, ○, ×, and △ represent the cases in which the shaking frequencies are 25, 40, 50, and 60 Hz, respectively. These were obtained by classical simulation of atomic motion in the radial direction with the same parameters as in the present experiment ($B_0 = 1.2$ G, $B_r' = 180$ G/cm, and $B_z'' = 140$ G/cm^2). The solid line in the inset shows the initial amplitude q_0 dependence of the oscillation frequency $\omega(q_0)/2\pi$, and the dotted line shows the case in which the potential is approximated to be linear.

in the trap. On the other hand, a magnetic trap is much deeper and wider than an optical trap, and, moreover, by using a RF magnetic field we can arbitrarily change the cutoff energy of the trap without changing the trap shape. Owing to these advantages we successfully observed the dynamics of the atom cloud directly, and obtained the evidence of the energy selective excitation as shown in Fig. 3.

In an optical trap, heating induced by the laser pointing noise has been theoretically investigated [13]; however, the energy selectivity in the excitation has not been studied. In contrast, we used the controlled shaking of the magnetic trap and observed the energy selectivity and the cooling successfully. Similar energy selective excitation and cooling are expected to be possible in an optical trap also. As seen in Fig. 2(b) this cooling cannot work when the temperature of the atom cloud is much lower than the trap depth. However, even in such a case, by chirping ν_s from higher to lower frequency it is expected to be possible to remove energetic atoms out of the deep trap and cool the remaining atom cloud further.

In conclusion, we have reported that an atom cloud confined in a magnetic trap was cooled by shaking the trap. This cooling effect is a consequence of the energy selective excitation of trapped atoms and the evaporative escape of the heated atoms. The energy selectivity of the excitation is due to the anharmonicity of the trap potential. The experimental evidence of this energy selective excitation has been directly observed owing to the large size and high controllability of the magnetic trap. Through the cooling the phase-space density was increased by a factor of about 2. We believe that, by optimizing the trap potential and shaking frequency, we can improve the cooling efficiency.

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[8] The atom number and temperature as functions of the shaking frequency ν_s varied with the shaking amplitude Δ. At a larger Δ, the depletion in the atom number as a function of ν_s was deeper and wider, and the depletion at the second harmonic was more significant. In the ν_s dependence of the temperature, the dispersion-shaped resonance was also observed, but the frequency width of this resonance was wider. In the following, we will discuss only the case of $\Delta = 0.5$ mm, which is a typical value in the present experiment.

[9] The atom number and temperature as functions of the shaking frequency ν_s did not change even when the minimum magnetic field (i.e., the magnetic field at the trap center) was increased from 1.2 G to 3.7 G. At this minimum magnetic field the trap potential around the center was reduced, and the oscillation frequencies ω_r and ω_a were decreased to $2\pi \times 120$ Hz and $2\pi \times 16$ Hz, respectively.

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