Cooling induced by parametric resonance in a magnetic quadrupole trap

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It is demonstrated experimentally that the anharmonic property of the quadrupole trap can be exploited to cool trapped atoms by modulating the trap potential anisotropically. This cooling effect arises from the energy-selective removal of the most energetic trapped atoms and the thermal equilibrium of the remaining atoms. The frequency dependences of the temperature and the fraction of the atoms left in the trap after the modulation are explored. It is also demonstrated that the cooling induced by parametric resonance can also increase the phase space density of the trapped atoms.

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Because of long interaction time and neglectable Doppler broadening, cold samples with large numbers of atoms have enormous potential for yielding new physics and new techniques. And the ability of cooling and trapping atoms has led to dramatic advances in atomic physics, such as the observation of Bose-Einstein condensation (BEC)[1], Fermi degeneracy[2], atom lasers[3], and speed reduction and storage of light in atomic gas[4,5]. Several well-worked methods have been proposed to prepare cold atoms, such as buffer gas cooling[6], laser cooling[7,8] and evaporative cooling[9]. Recently, selective parametric excitation in an anharmonic trap has been proved to be a new tool for producing ultracold atoms[10,11].

Parametric excitation of the motion is generally considered to result in heating of the trapped atoms[12,13]. However, in an anharmonic trap, due to the variation of the trap frequencies with vibrational energy, a modulation of the trap at a single frequency will excite only a small fraction of the atoms with a definite energy. Taking advantage of this feature, the most energetic atoms can be selectively excited and ejected from the trap, and the remaining atoms reach a new thermal equilibrium and are cooled via elastic collisions. The cooling induced by an one-dimensional (1D) excitation has been observed in an optical trap[10] and a cloverleaf magnetic trap[11]. In this letter, we report the first observation of the cooling phenomenon induced by a three-dimensional (3D) excitation in a magnetic quadrupole trap which has been widely used to confine cold atoms and ions.

The experimental details are described as follows. Our vacuum system consists of a quartz cell and an ion pump (20 L/s). Typically, pressure of 1×10^{-7} Pa is reached in the vacuum region. We use the ultraviolet light-induced atom desorption (UV LIAD) as a flexible source of ^{87}Rb[14,15]. At first, cold rubidium atoms are pre-cooled and collected in a conventional magneto-optical trap (MOT)[16]. Two external cavity diode lasers are necessary to provide the cooling and the repumping light for magneto-optical trapping of atoms respectively. The cooling light is tuned 13 MHz below the $5S_{1/2}$, $F = 2 \rightarrow 5P_{3/2}$, $F' = 3$ transition. It is split into six beams, expanded to 1.5 cm in diameter, and has a total intensity of 47 mW/cm^2. The 0.7-mW/cm^2 repumping laser beam is tuned in resonance with the $5S_{1/2}$, $F = 1 \rightarrow 5P_{3/2}$, $F' = 2$ transition to prevent optical pumping of the atoms to the lower ground-state hyperfine level. The magnetic field used for the MOT is provided by a pair of anti-Helmholtz coils and has an axial gradient of 1.1 mT/cm. All stray magnetic fields are nulled (below 0.01 mT) by three pairs of Helmholtz coils. We typically load around 1×10^8 ^{87}Rb atoms in 5 s. Next, after turning off the magnetic field for the MOT, the frequency of the cooling light is detuned by another 60 MHz, simultaneously its total power is lowered to 11 mW/cm^2, and the atoms are further cooled with the polarization gradient cooling method[17]. After the process of laser cooling, the cold atoms are optically pumped toward the $F = 2$, $m_F = +2$ state by applying a 0.2-ms pulse of circularly polarized light in resonance with the $5S_{1/2}$, $F = 2 \rightarrow 5P_{3/2}$, $F' = 2$ transition. A small bias magnetic field of about 0.5 mT is required for providing the quantization axis. Then the cold atoms are transferred into the magnetic trap. The magnetic quadrupole field for trapping cold ^{87}Rb atoms is just generated by the MOT coils, and its axial magnetic field gradient is about 10 mT/cm at 8 A. The overall efficiency of the transfer from the MOT to the magnetic trap is around 30%, and typically 3×10^7 ^{87}Rb atoms are trapped.

After the loading into the magnetic trap, the cold atoms are thermalized for 1 s. Then we modulate the trap for 2 s by controlling the current of another pair of coils sinusoidally. The coils for modulating the trap are anti-Helmholtz configuration, whose center is superposed with the one of the MOT coils. And the symmetry axes of the two pairs of coils are perpendicular to each other. The modulation amplitude of the axial field gradient, denoted by B'_q, is typically 0.21 mT/cm. After modulating the magnetic trap, the cold atoms are thermalized for 1 s again and released from the trap by cutting off the current of the MOT coils (< 150 μs). The temperature

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and the number of atoms left in the trap are determined by using the fluorescence imaging method. To collect the fluorescence from the atom cloud, we use a single lens ($f = 200$ mm) as the imaging system and record the image of the cloud with a charge-coupled device (CCD) camera (Apogee KX1E).

The radial temperature of the atom cloud after the modulation as the function of the modulation frequency ν_{M} is shown in Fig. 1. The initial temperature of 145 μK is indicated by the dash line. As one may expect, at the modulation frequency ν_{M} larger than 25 Hz the atom cloud in the trap is heated by the anisotropic modulation. And there are two resonances in the temperature at 35 Hz and its double frequency 70 Hz. This phenomenon is very similar to the case of harmonic trap, which exhibits resonance at frequency $2\omega_{\mathrm{h}}/n$ (ω_{h} is the vibrational frequency of the harmonic trap, n is any natural number). But one also can see that at the frequency ν_{M} less than 25 Hz, especially at around 20 Hz, the atoms are cooled, which is unexpected in a harmonic trap. The radii of the atom cloud after the modulation also show similar characteristics (see Fig. 2).

These experimental results are easily interpreted by the anharmonicity of the quadrupole trap. The spacings of the energy levels of an atom in a quadrupole trap are uneven and non-monotonic, but they trend to be closer when the energy of the atom is increased[18]. From the standpoint of classic mechanics, the vibrational frequency of the atom in the trap varies with its energy, and the atoms with higher energy have lower vibrational frequencies. When the modulation frequency is high, the excited atoms mostly have comparatively low energy and are at the bottom of the trap. Once these atoms are excited, they are hard to escape from the trap, resulting in the increase of the mean energy of the atom cloud. On the contrary, while the trap is modulated at a comparatively low frequency, it is mainly the most energetic atoms that are excited. The excited hot atoms have more chance to reach the outer edge of the cloud and are easily ejected from the trap. Then the remaining atoms in the trap will be thermalized and reach a new equilibrium via the elastic collisions, resulting in the reduction of the temperature. This can be confirmed from the large resonance in the loss of atoms at around 20 Hz (see Fig. 1).

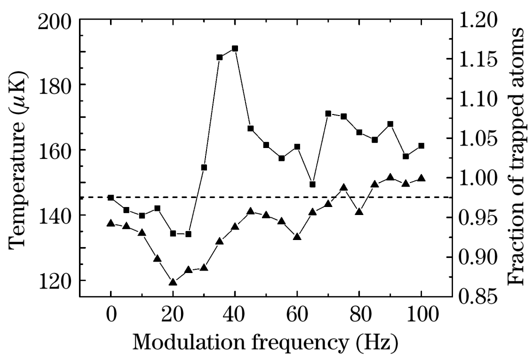

Fig. 1. Radial temperature (solid squares) and fraction of atoms left in the trap (solid triangles) after the anisotropic modulation versus the modulation frequency. The dashed line indicates the initial temperature.

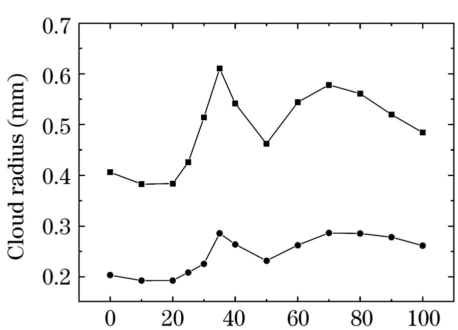

Fig. 2. Radial (solid squares) and axial (solid circles) radii of the atom cloud after the anisotropic modulation versus the modulation frequency.

Similar to evaporative cooling, cooling induced by parametric resonance decreases the mean energy of the atom cloud at the cost of the loss of only a small fraction of the trapped atoms. So it not only can decrease the temperature but also can increase the density of atom cloud, which can be deduced from the optical density of the atom cloud in the radial direction $\vec{y}$. Observing Fig. 3 one can see that modulating the trap at 20 Hz can increase the optical density D of the cloud. The optical density is related to the number density n by

$$D(x,z) = \sigma \int n(x,y,z)\mathrm{d}y, \tag{1}$$

where σ is the scattering cross-section. Assuming the density of the atom cloud has a Gaussian distribution, i.e.

$$n(x,y,z) = \frac{N}{\pi^{3/2}\sigma_x\sigma_y\sigma_z}\exp\Big(-\frac{x^2}{\sigma_x^2}-\frac{y^2}{\sigma_y^2}-\frac{z^2}{\sigma_z^2}\Big), \tag{2}$$

where N is the total atom number of the cloud, σ_x, σ_y and σ_z are the 1/e radii of the cloud along three orthogonal directions respectively, then the peak optical density is given by

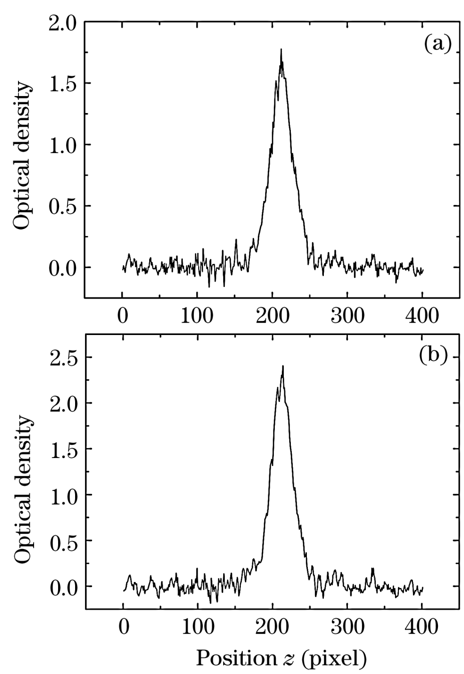

Fig. 3. Optical density profile of the cold rubidium atom cloud along the axial direction. (a) Without modulation; (b) after the modulation at 20 Hz.

$$D = \sigma \frac{N}{\pi \sigma_x \sigma_z} = n_0 \sigma \sigma_y \sqrt{\pi}, \quad (3)$$

here $n_0 = N/\pi^{3/2}\sigma_x\sigma_y\sigma_z$ is the peak density. We know from Fig. 2 that the radial radius σ_y of the cloud is decreased after a 4-s modulation at 20 Hz, so it can be deduced that the peak density n_0 is increased by the modulation (see Eq. (3)). And the phase space density of the cloud is related to temperature T and density n by

$$\rho_{\rm p} = n\lambda_{\rm db}^3 \propto \frac{n}{T^{3/2}}, \quad (4)$$

where $\lambda_{\rm db}$ is the deBroglie wavelength, so the cooling induced by parametric resonance can also increase the phase space density of the trapped atoms. In our experiment the phase space density is increased by a factor of about 1.5 when the trap is modulated at 20 Hz for 4 s.

There are two factors crucial for achieving cooling effect by the parametric resonance method. One is the finite depth of the trap, which must be moderate not only to allow the escaping of the excited atoms but also to hold a majority of the cold atoms in the trap. In our experiment, the depth of the magnetic trap is about 1.9 mK, which is mainly limited by the walls of the glass cell. The other one is the elastic collision rate, which must be large enough to allow a fast replenishment of the truncated energy distribution. In our experiment, the limit of the current through the trap coils prevents the achieving of lower temperature and higher phase space density by this cooling mechanism. Finally it should be emphasized that, although the parametric resonance can be exploited to cool trapped atoms without reducing the trap depth, in actual application it had better be used combining with evaporative cooling. That is because that, through several truncation-replenishment cycles, the populations of the levels in resonance are almost exhausted, and the process of cooling has to be terminated. So we have to ramp the modulation frequency up, simultaneously lower the depth of the trap, to cool the atoms further.

In conclusion, we have demonstrated that the atoms confined in a magnetic quadrupole trap can be cooled by modulating the trap anisotropically. The cooling effect relies on the energy-selective excitation and the escaping of the most energetic atoms. And this selective removal mechanism is a sequence of the anharmonicity of the potential. Benefitting from the selective excitation of the external degrees of freedom, this cooling mechanism can be extended to cool any particles trapped in any anharmonic trap. And it is capable of cooling mixtures of different species and isotopes provided that their oscillation frequencies are close to each other. Different from evaporative cooling, the depth of the trap need not to be reduced in the cooling process. In addition, combing with evaporative cooling mechanism, the cooling induced by parametric resonance is possible to become a more efficient and more powerful tool for cooling atoms, ions and molecules.

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