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Downward the temperature scale

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***Abstract*. Approaches to deep cooling of atomic gases are discussed. The delta kick cooling and adiabatic expansion as well as the limitations of the former are considered. The applicability of hollow optical dipole traps based on radiation of near-resonance transition frequency in atoms is shown. The possibility of designing such traps with a size of ~1 mm is analysed and the prospects for their use for cooling atoms by evaporation and adiabatic expansion are discussed.**

Keywords: *laser cooling, low temperatures, dipole force.*

Two significantly different approaches to lowering temperature can be distinguished. The first one is based on doing work by a cooled body, as, for example, is the case in adiabatic expansion of a gas or thermoelectric effect [1]. Cooling is especially effective if the body changes its phase state in the course of doing work, which occurs in the vapour compression cycle [2], in demagnetisation [3], in the course of anomalous liquid-crystal phase transition for ^{3}He [4], or in the dissolution of ^{3}He in ^{4}He [5]. The second approach is the velocity-selective effect on the body particles. In particular, evaporation removes the most energetic particles, while the remaining ones collide and rearrange into a thermal distribution with a lower temperature. Another method of selective impact is laser cooling of gases [6–9]. In contrast to evaporative cooling, interparticle interaction is not required here; only interaction of particles with radiation is sufficient. The lowest temperature having been achieved by any means is 500 pK [10]. This temperature was obtained in a cloud of 2500 atoms. In the experiment, several cooling methods were combined, but the basis was laser cooling of gas by resonance radiation, which made it possible to reduce the temperature from 600 K to 100 μK. At the subsequent stages, cooling by evaporation and adiabatic expansion was used.

This work is dedicated to the discussion of limitations that arise in the course of cooling of the atomic gases, and ways to overcome those limitations.

The delta kick cooling technique [11] is considered promising for further temperature reduction. The schematic of the method is shown in Fig. 1. At the initial time moment $t = 0$ (Fig. 1a), the gas that was previously held in thermal equilibrium in a harmonic potential is released into the free space by switching off the potential, and spreads up to the time moment $t = T$ (Fig. 1b). The ideal gas expansion produces a narrow distribution, which is then additionally 'turned' in the phase plane by a short action of the potential field $U = m\omega_x^2 x^2/2$. As a result, a distribution arises (Fig. 1c), having a substantially lower kinetic energy than the original one. The resulting system can be fixed in a new thermodynamically equilibrium state by switching on an appropriate harmonic potential.

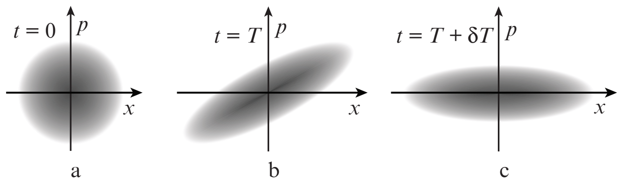

Figure 1. Delta kick cooling. Distribution in the phase space at key cooling moments: (a) $t = 0$, gas release from the harmonic potential; (b) $t = T$, after the collisionless gas expansion; and (c) $t = T + \delta T$, after a short exposure to the harmonic potential.

From the viewpoint of natural temperature scale expressed in terms of the Fermi energy E_F, the delta kick cooling does not lead to any result, since the T/E_F value does not change, although both the numerator and denominator decrease. Of course, the Fermi energy can also be introduced for bosons: $E_F = \hbar^2(6\pi^2 n)^{2/3}/(2m)$, where m is half the mass of a boson and n is the characteristic concentration of bosons (for example, at the cloud centre). The Bose condensation temperature can also be expressed in terms of Fermi energy: $T_{BEC} \approx 0.2E_F$. Although the value of T/E_F remains unchanged, lowering the absolute value of T is of importance because a cold cloud can be used to cool another system by bringing the two systems into contact.

The efficiency of delta kick cooling is shown not only for a noninteracting gas, but also for a wider class of systems, i.e. for clouds that expand in self-similar regime after the parabolic trapping is switched off [12]. Such systems include Fermi and Bose gases at zero temperature, the spatial distribution of which is described by the Thomas–Fermi profile, and also Fermi gas at an arbitrary temperature in the unitary regime of s-interactions [13]. At the end of expansion, the cloud should be intercepted again by a potential field of parabolic or near-parabolic type. The deviation from self-similar expansion leads to a decrease in the phase density after placing the gas into the final potential and the formation of a new equilibrium state with a higher T/E_F ratio than in the initial gas. An example of self-similarity violation is the Bose condensate

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expansion at a finite temperature: both the condensate and thermal fraction fly apart, though self-similarly (in the absence of interaction between them), but in different ways.

The lack of the possibility of cooling a spatially homogeneous gas initially trapped in a potential of rectangular shape is a limitation of the delta kick cooling technique. At the same time, homogeneous quantum gases are of interest for a number of reasons. First, the inhomogeneity limits the correlation radii near the phase transitions. Secondly, for Fermi gases being partially spin-polarised, spatial homogeneity opens up the possibility for observation of the Fulde–Ferrell–Larkin–Ovchinnikov superfluidity [14, 15] and pairing in the p-channel according to the Kohn–Luttinger mechanism [16–18]. These effects are not observed in a parabolic trap because most likely they 'lose out' to the effect of phase separation into the fully paired and fully spin-polarised gas. Recently, it has been reported on the preparation of homogeneous Bose [19] and Fermi gases [20, 21].

Adiabatic expansion is another method used to lower the temperature. In this case, as in the case of delta kick cooling, phase density and T/E_{F} ratio remain virtually unchanged. At the same time, there are a number of advantages. This method is not limited to the use of only parabolic or near-parabolic potentials, does not require the self-similarity of expansion, and is applicable in the important case of gas trapping in a rectangular-well potential. In technical terms, adiabatic expansion is simpler than that in the case of delta kick, since there is no need in reconciling several effects in place and time: original parabolic potential, delta kick potential, and final potential for stationary trapping.

Consider in more detail the applicability of adiabatic expansion to the homogeneous quantum gases trapped in a potential with almost vertical walls. The light fields for the formation of such a potential are shown in Fig. 2a. A cylindrical tube restricts the motion of atoms in the xy plane, and the motion along z axis is bounded on both sides by flat walls. Traps of this type were used for the preparation of quantum gases in work [19, 20]. A tube-shaped beam can be obtained using the scheme shown in Fig. 3. The tube diameter can be varied [22], which opens up a possibility of controlling the trap size and the cooling process by means of adiabatic expansion. The light fields form a repulsive dipole potential; for this, the laser radiation frequency ω must be higher than the frequency ω_0 of the strongest electro-dipole transition in the atom. The dipole force potential is related to the light intensity profile $I(r)$ by the expression [23]

$$U(\boldsymbol{r}) = \frac{3\pi c^2 \Gamma I(\boldsymbol{r})}{2\omega_0^3(\omega - \omega_0)}, \qquad (1)$$

where Γ is the inverse lifetime of the excited state of the atom.

In experiments [19, 20], the sizes of hollow traps were not large, i.e. of the order of 100 μm. As an example, in work [19] trap was 75 × 35 × 35 μm in size. In quantum gases, the interatomic distance ranges from hundreds of nanometres for weak s-repulsion to 1 μm in the case of strong interactions. Such a trap contains 10^5–10^7 atoms. As the interparticle distance decreases, three-particle inelastic collisions become noticeable, thus leading to a loss of particles from the trap and heating of the remaining particles [24, 25]. Increasing the trap size and, accordingly, the number of particles in the trap is of interest, since the smallest value of T/E_{F} is scaled as $1/N^{1/3}$. This scaling is due to the fact that the distance between the energy levels near the chemical potential can be taken as a minimum value of T. From the viewpoint of increasing the number N of particles, large traps (about 1 mm in size) are also of interest due to the fact that they would make it possible to completely load all atoms trapped in a magneto-optical trap at the first stage of cooling. When using a dipole trap with trapping in the maximum intensity region, only a small part of atoms is commonly loaded from a magneto-optical trap [26, 27], although, for lanthanide atom, there is an example of loading more than half the particles [28]. Large hollow

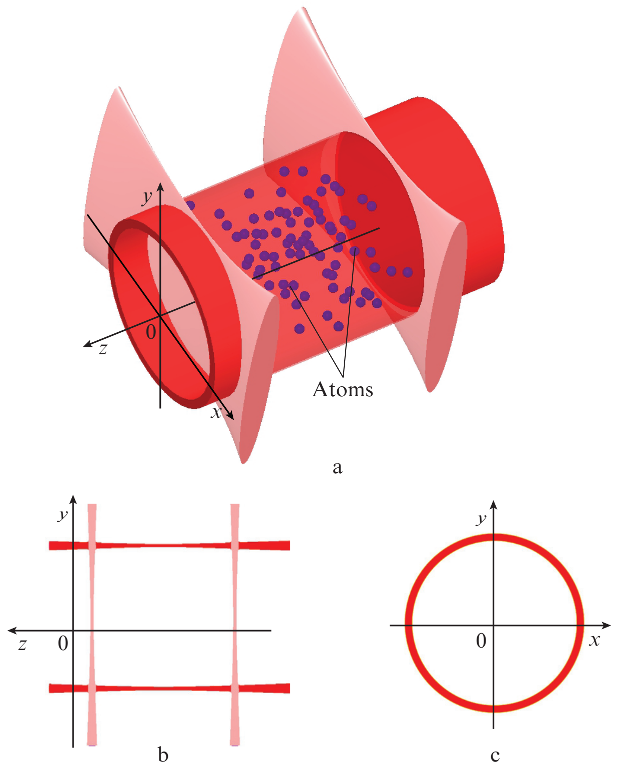

Figure 2. (a) Trapping of atomic gas in the space bounded by radiation beams and (b, c) beam cross section by (b) yz and (c) xy planes.

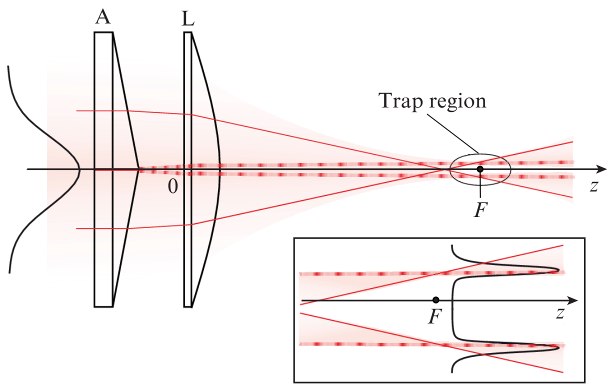

Figure 3. (Colour online) Optical scheme for obtaining a light tube from a beam with a Gaussian transverse mode (shown by the black curve): (A) axicon; (L) lens (set in the $z = 0$ plane); (F) focus of the lens. Red lines and shadow show the course of rays in the geometric optics approximation, and the dotted line shows the trajectories of the rays emerging from the axicon centre. The beam takes the form of a tube near the lens focus. The black curve in the inset shows the intensity distribution in the $z = F$ plane.

traps may also be of interest for the undisturbed trapping of Rydberg atoms [29, 30].

Large hollow traps similar to those shown in Fig. 2 have not yet been developed. The limitations are associated with the laser radiation power and detuning of the frequency ω from the resonance frequency ω_0. As can be seen from formula (1), insufficient power and large frequency detuning restrict the potential height. In [19, 20], the frequency detuning $\omega - \omega_0$ was very significant: $(\omega - \omega_0)/\omega_0 \approx 0.5$ and 0.3, respectively. This imposes strict requirements on the intensity, since the ratio $I/(\omega - \omega_0)$ determines the potential height $U_{\max}$. The choice of a large detuning value is necessary to minimise Rayleigh scattering, the rate of which

$$\Gamma_{\mathrm{R}} = \frac{3\pi c^2 \Gamma^2 I}{2\hbar\omega_0^3(\omega - \omega_0)^2} \quad (2)$$

decays quadratically with increasing detuning [23].

The use of light with a small frequency detuning $\omega - \omega_0$ makes it possible to design a large-volume trap and ensure the Rayleigh scattering within acceptable limits for cooling. We show this by the example of a lithium-6 atom, for which the resonance wavelength is $2\pi c/\omega_0 =$ 671 nm. Consider a trap employing radiation at a wavelength of $2\pi c/\omega$ = 669 nm, which, at the full trap wall thickness of 16 μm (by the intensity level of 1/2) and a diameter of 1 mm, ensures the potential height $U_{\max}$ = 150 μK, which is sufficient to intercept most of atoms from the magneto-optical trap when using a laser beam with a power of 1.3 W. Given the energy contribution of Rayleigh scattering, which is approximately equal to $\hbar^2\omega^2/(mc^2)$ per single scattering event, it is possible to find the gas heating rate. Assuming that the trap is filled to $U_{\max}$, we obtain that the energy E of the trapped atom increases with velocity:

$$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\mathrm{R}} = \frac{\hbar^2\omega^2}{mc^2}\frac{\alpha}{2}\Gamma_{\mathrm{R}}^{\max} = \frac{\hbar\omega^2\Gamma}{2mc^2}\frac{\alpha U_{\max}}{\omega - \omega_0}, \quad (3)$$

where α is the ratio of the volume of walls to the trap volume and $\Gamma_{\mathrm{R}}^{\max}$ is the frequency of Rayleigh scattering on the surface of maximum intensity. Within this trap configuration, this gives a heating rate of $0.15U_{\max}$ per second, which can be overcome by rapid cooling. Without loss of particles, this cooling is attained by the superposition of optical molasses [31], which causes a temperature decrease down to 40 μK or less during 1 ms [32]. Cooling can be continued with the loss of particles by evaporation [33]. When the gas energy decreases during cooling, the heating rate drops. In addition, when the gas temperature decreases, the required level $U_{\max}$ can be reduced by an increase in the detuning value $\omega - \omega_0$, which leads to an additional decrease in Rayleigh heating.

To change the size of hollow traps, both a shift of flat walls and a change in the tube diameter performed by means of projection optics or more complex schemes are used [22].

Thus, hollow traps, like the one shown in Fig. 2, make it possible to trap a large number of atoms and to conduct both evaporative cooling and cooling with adiabatic expansion. Under conditions of limited laser power, a large trap volume is attained by using near-resonance radiation. At the same time, it turns out possible to limit the gas heating caused by Rayleigh scattering.

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