A Proposal for Optically Cooling Atoms to Temperature of 10^{-6} K

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We propose an optical method for the three-dimensional cooling of collections of atoms to extremely low temperatures. With this method it should be possible to cool sodium atoms to temperatures of 10^{-6}K or less. These low temperatures correspond to velocities less than the recoil velocity of an atom emitting a single resonant photon. Although the method is straightforward in principle, it anticipates the demonstration of optical traps capable of localizing (trapping) atoms within small regions of space (dimensions on the order of 1-100μm) and of cooling them to temperatures on the order of the "quantum limit" $kT=\hbar\gamma/2$, where γ is the natural linewidth of the resonant transition. The recent laser cooling of sodium atoms to the "quantum limit" of 2.4 $\times10^{-4}$K [1] suggest that this prerequisite will be met in the near future. Several schemes have been proposed previously for the cooling of magnetically trapped atoms to temperatures below $\hbar\gamma/2$.[2], [3]. The magnetic trapping of sodium atoms [4] opens up the possibility for trying those schemes.

Our scheme is simply described as follows. Consider an ensemble of atoms tightly confined within a small region of space by a small optical trap and laser-cooled to a temperature of $kT=\hbar\gamma/2$. At time t=0 the small, tight optical trap used to localize the atoms is turned off and is replaced by a loose trap that will allow the atoms to expand into a larger volume. The atoms are initially centered in the potential minimum of the new trap; as time proceeds they execute harmonic oscillatory motion in that trap. Assuming that the trap is an ideal harmonic potential well and that all the atoms start from the exact center of the trap, all the atoms will reach their turning points (velocity=0) at the same time, equal to 1/4 of the harmonic oscillator period, irrespective of their initial velocities. At this time the trapping light is turned off and all the atoms come to rest simultaneously at zero temperature.

There are several factors that place limits on the ultimate temperature that can be achieved by this scheme. (i) Any atom in the trap must not scatter a photon in a time corresponding to 1/4 of the harmonic oscillator period. This constraint requires the use of dipole force trap [5] where the laser is tuned far from resonance. (ii) Given an initial spread of atoms to dimensions Δx_i and an initial velocity spread of Δv_i, Liouville's Theorem states that the final velocity spread can be reduced to $\Delta v_f=(\Delta x_i/\Delta x_f)\Delta v_i$. (iii) Practical traps always have anharmonic components to the potential. so that the atoms will not come to rest simultaneously. Thus, the motion of the atoms must be confined to the central (harmonic) portion of the trap. Given a fixed amount of tunable laser power, the above conditions determine a lower temperature limit.

A three-dimensional optical trap using the dipole force of radiation pressure can be formed by three intersecting and mutually perpendicular tightly colliminated laser beams. We choose to use TEM^*_{01}-mode

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laser beams having an intensity distribution given by $I(r)=I_0(r/w_0)^2\exp(-2r^2/w_0^2)$, where r is the transverse coordinate. The use of three such beams forms a nearly radially symmetric trap for displacements small compared to w_0. The use of TEM^*_{01} laser beams is preferred over TEM_{00} beams, since the atoms are confined to regions of low light intensity, thus minimizing the problem of heating by spontaneous scattering. As a concrete example, consider a laser power of 1W and an initial atomic spread of 1.3μm. This localization can be obtained using a confining trap $4x10^2 h\gamma$ deep with a radius of 37μm. We find that for a expansion trap of w_0=130μm and a laser detuning from resonance of 24.5 GHz, the final temperatures predicted by anharmonicities and by phase space considerations are both equal to $5x10^{-7}$ and that each atom scatters one photon on average. Similarly, for a laser power of 0.2W, the values w_0=80μm and a detuning of 17.4 GHz yield final temperatures of ~1μK.

There are other ways to use the properties of harmonic traps to cool atoms. (1) Consider a pulsed version of the above scheme. In this techique the atoms are allowed to expand into free space when the tight small trap is turned off. At some later time, the large loose trap is pulsed on for a short period time. For a harmonic trap the impulse delivered to an atom at position r is proportional to r, as is the atom's velocity. Thus, by correctly choosing the pulse energy all atoms may be brought nearly to rest. Provided the pulse energy and mode structure of the pulsed laser can be controlled, cooling to temperatures below 10^{-7}K can be achieved. (2) The traps can be made more harmonic by combining trapping and antitrapping potentials analogous to optical lens correction by using both converging and diverging lenses. (3) After localizing the atoms in a small deep trap, a shallow compact trap can be used to let the high speed tail of the Boltzman distribution escape. The rms velocity of the remaining atoms is decreased. If the atoms are then allowed to cool by the harmonic expansion technique, temperatures in the nanokelvin range may be obtainable.

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