

Collision-assisted Zeeman cooling of neutral atoms

G. Ferrari^a
 Laboratoire Kastler Brossel, Département de Physique de l'École Normale Supérieure, 24 rue Lhomond,
 75231 Paris Cedex 05, France

and

INFN sezione Firenze, largo E. Fermi 2, 50125 Firenze, Italy

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Abstract. We propose a new method to cool gaseous samples of neutral atoms. The gas is confined in a non dissipative optical trap in the presence of an homogeneous magnetic field. The method accumulates atoms in the $m_F = 0$ Zeeman sub-level. Cooling occurs *via* collisions that produce atoms in $m_F \neq 0$ states. Thanks to the second order Zeeman effect kinetic energy is transformed into internal energy and recycling of atoms is ensured by optical pumping. This method may allow quantum degeneracy to be reached by purely optical means.

PACS. 32.80.Pj Optical cooling of atoms; trapping – 32.60.+i Zeeman and Stark effects – 03.75.Fi Phase coherent atomic ensembles; quantum condensation phenomena

Since the first proposal of optical pumping [1] many authors have focused on different schemes to cool samples by means of laser light [2] and external fields [3, 4]. Laser cooling has produced significant results both for macroscopic and microscopic systems.

Spontaneous anti-Stokes scattering has been used to cool molecular gasses, fluid solutions and solid states systems [5–7]. However these cooling schemes have intrinsic limitations in the attainable temperature due to the reduction of anti-Stokes scattering at low temperatures.

In the microscopic domain laser cooling has been very efficient on gases of ions and neutral atoms [8]. Associated with evaporative cooling [9, 10], laser cooling was an essential step towards Bose-Einstein condensation of weakly interacting gases [11, 12]. For neutral atoms polarization gradient cooling in optical molasses reaches temperatures on the order of $10 T_r$ ($T_r = \hbar^2 \mathbf{k}^2 / m k_B$ is the single-photon recoil temperature, \mathbf{k} is the photon wave-number). Sideband cooling in 3D has reached $1.5 T_r$ and the limitation by multiple photon scattering has been identified [13, 14]. 3D sub-recoil cooling [15] has reached $T_r/20$ for free atoms but suffers from a loss of efficiency for trapped atoms at high density [16]. In contrast evaporative cooling takes advantage of elastic collisions and does not have limitations due to light scattering. It only suffers from a significant loss of atoms during evaporation.

In this article we propose a new cooling mechanism that combines elastic collisions, inelastic collisions and op-

tical pumping to efficiently cool samples of neutral atoms with no loss of atoms. In principle the method is able to reach sub-recoil temperatures and hold promises to reach quantum degeneracy by purely optical means. The key points of the method are the following: (i) the gas is stored in an optical far-off resonance trap (FORT) [17] in a well defined Zeeman sub-level of the electronic ground state, (ii) a uniform magnetic field is applied to the sample and its magnitude is chosen to have the second order Zeeman energy on the order of $k_B T$, (iii) inelastic collisions produce atoms in different Zeeman sub-levels of higher energy transforming kinetic energy into internal energy, (iv) atoms are then optically pumped back to the initial state by an additional laser beam with suitable polarization. Such a cycle removes an energy on the order of the second order Zeeman energy and cooling occurs at a rate set by the collision rate.

Now we apply the method to an alkali atom with nuclear spin $3/2$ (such as ${}^7\text{Li}$, ${}^{23}\text{Na}$ or ${}^{87}\text{Rb}$). The energy shifts of the different Zeeman sub-levels in a uniform magnetic field B can be calculated using:

$$\xi = \frac{\mu_B B}{2\hbar\omega_{\text{HF}}} = \frac{\omega_L}{\omega_{\text{HF}}} \quad (1)$$

where μ_B is the Bohr magneton, $\hbar\omega_L$ is the linear Zeeman shift between adjacent Zeeman sub-levels and $\hbar\omega_{\text{HF}}$ is the hyperfine splitting of the electronic ground state. The Zeeman corrections to second order in ξ read:

$$\delta_{F, m_F}(\xi) = (-1)^F [\hbar\omega_{\text{HF}} m_F \xi + \hbar\omega_{\text{HF}} (4 - m_F^2) \xi^2]. \quad (2)$$

Assume that the gas is polarized in the level $|F = 1, m_F = 0\rangle$ and sufficiently cold that only *s*-wave collisions take

^a e-mail: gabriele.ferrari@lkb.ens.fr
 or e-mail: ferrari@lens.unifi.it

Present address: European Laboratory for Non-Linear Spectroscopy, largo E. Fermi 2, 50125 Firenze, Italy.

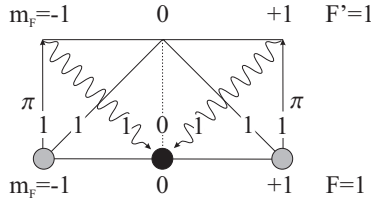


Fig. 1. Scheme for the cooling in an hyperfine state with negative Landé factor. Collisions between atoms in $|F = 1, m_F = 0\rangle$ (black round) produce couples of atoms in $|F = 1, m_F = \pm 1\rangle$ of higher internal energy (grey). Energy conservation in the collision is ensured by reduction of the kinetic energy of the relative motion. Optical pumping on a $F = 1 \rightarrow F' = 1$ transition with π polarized light brings the atoms back to the initial state. In the sketch are indicated the squares of the Clebsch-Gordan coefficients multiplied by 2.

place [18]. The projection of the angular momentum on the quantization axis is conserved, hence a colliding pair of atoms either remains in the same internal state (A), or changes the internal state to the pair $|F = 1, m_F = -1\rangle + |F = 1, m_F = +1\rangle$ (B). Those collisions have already been observed in [19]. The total internal energy of the pairs A and B are equal to first order in ξ but differ to second order: $E_A(\xi) = -8\xi^2\hbar\omega_{\text{HF}}$, $E_B(\xi) = -6\xi^2\hbar\omega_{\text{HF}}$. Since $E_A(\xi) < E_B(\xi)$, couples of $|F = 1, m_F = 0\rangle$ atoms may collide and change the internal state only when their energy in the center of mass is greater than the energy threshold $\Delta = E_B(\xi) - E_A(\xi)$. This endo-energetic collision (EC) transforms a fraction of kinetic energy into internal energy. The cycling on EC's is insured by a π -polarized laser resonant on a $F = 1 \rightarrow F' = 1$ optical transition. $m_F = 0$ atoms are not coupled to the pumping light (see Fig. 1) while $m_F = \pm 1$ atoms once excited in $|F' = 1, m_F = \pm 1\rangle$ may decay with a 1/2 branching ratio to A [20]. The efficiency of the cooling process will depend on the ratio of the removed energy and heating on each cycle: the pumping process will heat the sample due to the recoil of the atom after the absorption and spontaneous emission of the pumping photon. In fact two different situations can be considered: the temperature is much larger than the recoil energy $k_B T \gg E_r$ ($E_r = k_B T_r/2$), or the two are similar $k_B T \sim E_r$ [21]. In the first case the heating associated with the pumping can be neglected and the cooling is then equal to the rate of EC times the removed energy in each collision. In the low energy domain the energy balance of the cooling will also include the heating associated with the pumping process.

As stated above, the cooling rate depends on the rate Γ at which EC's take place and the amount of the energy removed. To calculate Γ , we consider the gas as a classical homogeneous gas and we determine the fraction of collisions with energy in the center of mass E_{CM} greater than the removed energy Δ :

$$\Gamma(\Delta, T) \propto \sigma \int d\mathbf{p}_1 d\mathbf{p}_2 n(1, T)n(2, T) \times \Theta(E_{\text{CM}} - \Delta) |\mathbf{v}'_1 - \mathbf{v}'_2|, \quad (3)$$

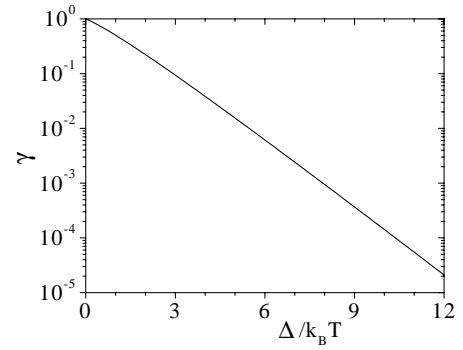


Fig. 2. $\gamma(\Delta/k_B T) = \Gamma(\Delta, T)/\Gamma(0, T)$ is the normalized rate of collisions with energy in the center of mass greater than the energy threshold expressed in temperature units.

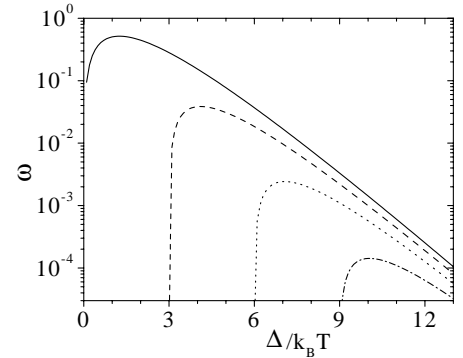


Fig. 3. $\omega = (\Delta - E_p)\gamma(\Delta/k_B T)/(k_B T)$ is the cooling rate in units of temperature and collision rate at zero threshold. $E_p = 0$ (solid line), $E_p = 3k_B T$ (dashes), $E_p = 6k_B T$ (dots), $E_p = 9k_B T$ (dash-dots).

where σ is the cross section for a collision changing the internal state, 1 and 2 represent the two colliding atoms, $n(i, T)$ is the Boltzmann factor for atom i at temperature T , Θ is the step function equal to 1 if $E_{\text{CM}} > \Delta$ and null otherwise, and \mathbf{v}'_i is the velocity of atom i after the changing of the Zeeman sub-level. The factor $|\mathbf{v}'_1 - \mathbf{v}'_2|$ in equation (3) takes in account the reduction of the density of final states when the energy in the center of mass changes during the collision [22].

Figure 2 shows $\gamma(\Delta/k_B T)$, *i.e.* the rate $\Gamma(\Delta, T)$ normalized by the collisional rate at zero energy threshold $\Gamma(0, T)$. If we define E_p as the energy gained during the pumping process (typically few E_r), in the limit where the pumping is faster than $\Gamma(\Delta, T)$ the cooling rate W reads:

$$W(\Delta, T, E_p) = \Gamma(\Delta, T)(\Delta - E_p). \quad (4)$$

Those rates are plotted in Figure 3 for different amounts of heating associated with the pumping. One finds that for different values of $E_p/k_B T$, the cooling rate is optimized when $\Delta \simeq k_B T + E_p$. Then it is possible to make an estimation of the dynamics of the cooling process by solving

$$\frac{dT}{dt} = -\frac{(\Delta - E_p)}{6k_B} \Gamma(\Delta, T) \quad (5)$$

$$= -\frac{T_{\text{in}}}{6} \Gamma(0, T_{\text{in}}) \gamma\left(1 + \frac{E_p}{k_B T}\right), \quad (6)$$

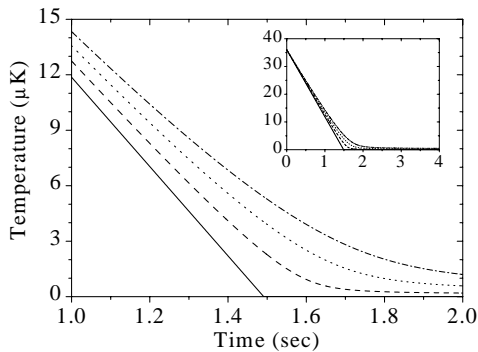


Fig. 4. Cooling dynamics of a gas of ^{87}Rb atoms initially at $36\ \mu\text{K}$ and $2 \times 10^{11}\ \text{cm}^{-3}$ peak density for different pumping energies E_p . The gas is confined in an harmonic potential and the cross section for EC's is supposed to be on the same order as that for elastic collisions. $E_p = 0$ (solid line), $E_p = 6E_r$ (dashes), $E_p = 12E_r$ (dots), $E_p = 18E_r$ (dash-dots). The inset shows the same picture on a different time scale.

where T_{in} is the initial temperature after the loading of the FORT. The denominator in equation (5) takes into account the heat capacity of a 3D confined gas and the fact that the energy subtracted in EC is provided by the two colliding atoms. In equation (6) we use the fact that if the trapping potential is harmonic (like the bottom of a FORT) $\Gamma(0, T) \propto T^{-1}$. The dynamics of the cooling behaves differently in the two temperature regimes: if $E_p/k_B T \ll 1$ the argument of γ is constant therefore the temperature decreases linearly. Once $E_p/k_B T \simeq 1$ the normalized collision rate γ is no longer constant and since it can be approximated by an exponential function (see Fig. 2) the temperature decreases logarithmically with time.

As an example we consider a gas of ^{87}Rb at $36\ \mu\text{K}$ and $2 \times 10^{11}\ \text{cm}^{-3}$ peak density (typical values attainable after charging a FORT from a magneto-optical trap [8]). If we suppose that the collisional cross-section for collisions changing the Zeeman sub-level is of the same order as those for elastic collisions [23] we find $\Gamma(0, T_{\text{in}}) \sim 4\ \text{s}^{-1}$. In Figure 4 are plotted the integration of equation (6) for values of E_p ranging from 0 to $18E_r$ ($E_r = 180\ \text{nK}$ for ^{87}Rb). For this choice of parameters the temperature drops almost linearly during the first two seconds. After the first 2 seconds typically we find $T \simeq E_p/4k_B$ and after 3 seconds $T \simeq E_p/6k_B$. At longer cooling times $T \propto [\log t]^{-1}$ and reaches $E_p/12k_B$ after 50 seconds. The present simulation will not be valid in the regime of extremely low temperature when the gas can no longer be treated as a classical gas and when the radiation trapping effect becomes extremely large. Experimentally Δ should be swept from a value corresponding to the initial temperature of the gas, to slightly more than E_p . To avoid any dependency of the optical potential on m_F , the trapping light has to be linearly polarized and propagating along the quantization axis. Slight imperfections in the polarization of the trapping light do not affect the physics discussed so far since they do not change the energy of colliding pairs of atoms if the projection of the angular momentum is conserved.

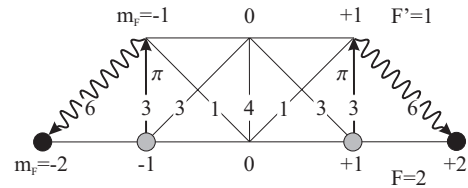


Fig. 5. Scheme for the cooling in an hyperfine state with positive Landé factor. Atoms in $|F = 2, m_F = \pm 2\rangle$ (black round) collide producing couples of atoms in $|F = 2, m_F = \pm 1\rangle$ of higher internal energy (grey) transforming part of the kinetic energy of the relative motion into internal energy. Optical pumping on a $F = 2 \rightarrow F' = 1$ transition with π -polarized light brings the atoms back to the initial states. In the sketch are indicated the squares of the Clebsch-Gordan coefficients multiplied by 10.

An important issue for the cooling is the control of the magnetic field \mathbf{B} . As stated before the direction of \mathbf{B} has to be well defined and parallel to the polarization of the pumping light. Indeed any misalignment results in a σ component in the polarization of the pumper that introduces further heating terms. Since the π component affects only $m_F = \pm 1$ atoms and the σ component affects the ensemble of the gas, choosing a Rabi frequency on the order of the rate of EC's will reduce the heating due to the imperfect polarization. The requirements on the intensity of \mathbf{B} are much less demanding. In order to cool ^{87}Rb ($\omega_{\text{HF}} = 2\pi \times 6.8\ \text{GHz}$) in the lower hyperfine state $F = 1$, the magnetic field necessary to have Δ corresponding to $100\ \mu\text{K}$ is $100\ \text{G}$. The intensity of \mathbf{B} is then swept down to slightly more than E_p , $\Delta \sim 1\ \mu\text{K}$ (a few times E_r). Since $\Delta \propto \mathbf{B}^2$, the magnetic field at the end of the sweep will be of the order of $10\ \text{G}$. It is worth noting that loss due to light-assisted collisions such as fine-structure or hyperfine-structure changing collisions can be avoided by choosing properly the pumping transition: pumping of ^{87}Rb on the $F = 1 \rightarrow F' = 1$ transition of the D1 line has no allowed channel for those collisions.

Other cooling schemes are possible for the same atoms in the higher hyperfine state (positive Landé factor g_F). Using equation (2) we find that the magnetic energy of the couple $|F = 2, m_F = \pm 1\rangle$ is $6\xi^2\hbar\omega_{\text{HF}}$ higher than that of couple $|F = 2, m_F = \pm 2\rangle$. Optical pumping on a $F = 2 \rightarrow F' = 1$ transition with π -polarized light (see Fig. 5) again permits cycling on EC's that lower $|m_F|$. A major obstacle to this type of cooling is represented by inelastic collisions changing the hyperfine state. Nevertheless it may remain feasible for particular choices of atoms: ^{87}Rb was proven to have the cross-section for spin-exchange collisions sufficiently small to make an unpolarized dilute cold gas stable [23].

This cooling mechanism can also be extended to alkali atoms with nuclear spin different from $3/2$, in the highest hyperfine state. As in the previous case the atoms are polarized in the extreme Zeeman levels $m_F = \pm F$ and EC's produce atoms in lower Zeeman levels. The pumping is done by a π -polarized laser resonant on a $F \rightarrow F' = F - 1$ transition. Other generalizations could consider mixtures of different atoms with different g_F factors. The cooling

would then take advantage of the first-order Zeeman effect.

The proposed cooling mechanism can be applied to produce Bose-Einstein condensates [11] with purely optical means. Since collisions between atoms in different Zeeman sub-levels do not give rise to trap losses, one can choose pumping rates arbitrarily low in order to fulfill the *festina lente* scenario [24] where the fluorescence rate is much smaller than the oscillation frequency of the atom in the trapping potential. The lower limit in the attainable temperature with this technique is presumably due to the reabsorption of scattered photons during the pumping phase. One possibility to partially avoid this effect is to reduce the dimensionality of the trapping potential in order to have an elongated cigar-shaped cloud [25].

In conclusion we have presented a new, simple and spin-polarizing cooling scheme that combines optical pumping, inelastic collisions and second order Zeeman effect. The combination of optical pumping and endo-energetic collisions permits to avoid the intrinsic limitation of laser cooling and evaporative cooling: the finiteness of the exchangeable momentum between atoms and photons, and the loss of atoms respectively. In presence of an homogeneous magnetic field, collisions allow a defined amount of kinetic energy to be transformed into internal energy (by changing the Zeeman state of the atoms) and optical pumping ensures the cycling on the process.

Finally it is interesting to note that the proposed cooling method, polarizing the atoms at will in the extremal Zeeman sub-level ($m_F = \pm F$) or $m_F = 0$, is well adapted to operation in atomic fountains. ^{87}Rb , which seems to be a valid candidate as a future frequency standard [26], fits all the requirements of the presented mechanism.

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