Cooling atoms in dark gravitational laser traps

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Alkali atoms repeatedly reflected by an evanescent light wave and kept in their lower hyperfine ground state by a weak repumping laser beam can be cooled to recoil-limited temperatures by a Sisyphus and a geometric cooling mechanism, which are connected with spontaneous transitions to the upper hyperfine ground state during the reflections. These effects can be used in gravitational laser traps to produce extremely cold and dense samples of atoms.

An evanescent light wave, which is formed by total internal reflection of a laser beam on the surface of a dielectric substrate, can act as a mirror for neutral atoms.[1–3] In addition to a broad current interest for atomic de Broglie wave optics,[4] such mirrors are also very promising for realizing new atom traps with unprecedented densities.

In the field of gravity, an atom can bounce on an evanescent wave many times and, if the surface is appropriately formed, a stable confinement is achieved.[5] In such gravitational laser traps the photon scattering rates can be very low ($\sim$10/s per atom) since the time an atom spends in the evanescent wave is short and the detuning can be very large. Therefore, the attainable density is not restricted by radiation trapping and excited-state collisions, as is the case in the widely used magneto-optical traps.[6]

The first experimental realization of a gravitational laser trap was reported by Aminoff *et al.*,[7] who observed up to ten bounces on a shallow curved mirror, without any cooling mechanism acting. The maximum $1/e$ storage time of about 100 ms was limited by heating processes with the recoil of a few scattered photons already leading to an escape.

We propose a novel, simple, and efficient cooling scheme for alkali atoms in a gravitational laser trap, which is based on an *inelastic* reflection from the evanescent wave. In this scheme two distinct mechanisms allow us to cool atoms to temperatures far below the Doppler limit in a nearly dark trap.

The basic idea is as follows (Fig. 1a): An atom entering the evanescent wave in the lower hyperfine ground state can make a transition to the less repulsive upper ground state by scattering an evanescent wave photon. The atom thus loses kinetic energy in the reflection process, similarly to the well-known Sisyphus effect[8,9] in standing-wave laser fields. After the reflection the atom is pumped back to the lower hyperfine ground state by a weak cw laser beam coming from above. The *directed* recoils of the absorbed photons

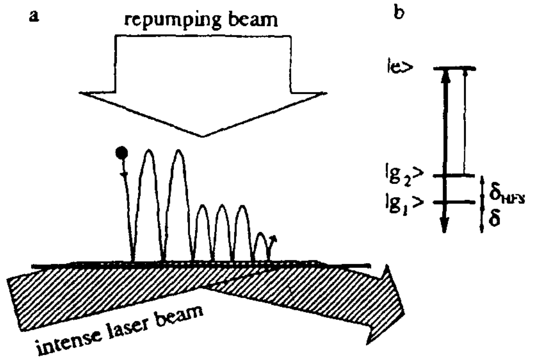

FIG. 1. Basic cooling scheme.

from the repumping beam slow the atom down, since the mean atomic velocity after the reflection is pointing upwards. Both the Sisyphus-type and the spontaneous geometric cooling mechanism alone would lead to final temperatures corresponding to ~20 recoil energies, although the time constant for the latter mechanism is generally longer.

We give a semiclassical description of the interaction of the atoms with the evanescent wave in the dressed-atom picture.[8] We have found[10] that, to a good approximation, the alkali atoms can be considered simply as three-level atoms with a single excited state and two hyperfine ground states split by $\hbar\delta_{\mathrm{HFS}}$ [Fig. 1b]. The evanescent wave laser beam is blue-detuned with respect to the lower ground state by δ and the weak repumping laser beam is resonant with the transition from the upper ground state.

The intensity of the evanescent wave is $I=I_0\exp(-2\zeta/\Lambda)$, where $\Lambda=\lambda/2\pi(n^2\sin^2\theta_i-1)^{-1/2}$ is the decay length, and θ_i is the angle of incidence. In the evanescent wave the states $|g_1,n+1\rangle$, $|g_2,n+1\rangle$, and $|e,n\rangle$ with $n+1$ and n evanescent wave photons are mixed with each other to form triplets of dressed states $|1,n\rangle$, $|2,n\rangle$, and $|3,n\rangle$ (Fig. 2).

First, we make the approximation that δ is much larger than the atomic line width, $\delta\gg\Gamma$. The coherences between the dressed states can then be ignored[8] and one can describe the spontaneous decay by random quantum jumps between dressed states. Second, the saturation parameter s is assumed to be small,

$$s=\frac{\omega_{\mathrm{R}}^2(\zeta)}{2\delta^2}\ll 1,$$

where $\omega_{\mathrm{R}}(\zeta)$ is the on-resonance Rabi frequency, which is assumed to be equal[10] for the two transitions, $|g_1\rangle\leftrightarrow|e\rangle$ and $|g_2\rangle\leftrightarrow|e\rangle$. Third, the probability p_{sp} for a reflection with spontaneous scattering is assumed to be small, $p_{\mathrm{sp}}\ll 1$, so that only one transition $|1,n\rangle\rightarrow|i,n-1\rangle$ can occur during a reflection.

The light shifts and the composition of the dressed states can be calculated in first order perturbation theory, giving a light shift of

$$U_1(\zeta)=\hbar\,\frac{\omega_{\mathrm{R}}^2(\zeta)}{4\delta}$$

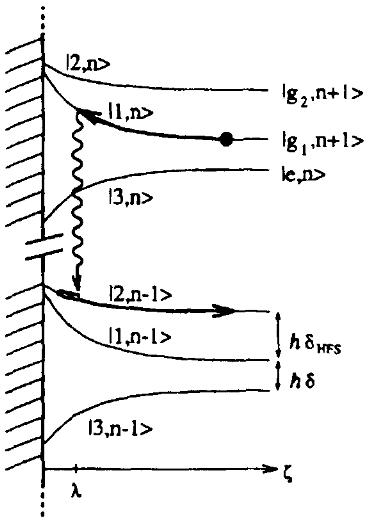

FIG. 2. Dressed energy levels of an alkali atom in an evanescent light wave. In the reflection process atoms can lose kinetic energy by making a spontaneous transition to the less light-shifted upper hyperfine level.

for the lower ground state and a light shift of the upper ground state that is smaller because of its larger detuning,

$$U_2(\zeta)=\hbar\,\frac{\omega_R^2(\xi)}{4(\delta+\delta_{HFS})}\,.$$

The dipole force experienced by an atom in a dressed state with a potential U_i is $\mathbf{F}_{dip}=-\nabla U_i$. An atom that approaches the glass surface in the lower ground state $|g_1,n+1\rangle$ adiabatically evolves into the repulsive dressed state $|1,n\rangle$ and is reflected if the velocity at which it hits the surface is not too fast. The dressed state $|1,n\rangle$ contains a small admixture of the excited state and may therefore decay to another dressed level. In this case it absorbs the momentum of the evanescent wave photon and suffers a recoil by the emitted photon in a random direction. Otherwise, the atom is reflected elastically.

The rates Γ_{1i}, for the spontaneous transitions $|1,n\rangle\rightarrow|i,n-1\rangle$ are calculated from the dressed state compositions to the lowest order in s,

$$\Gamma_{11}\approx q\,\Gamma\,s/2,$$

$$\Gamma_{12}\approx(1-q)\Gamma\,s/2,$$

$$\Gamma_{13}\approx\Gamma(s/2)^2.$$

Here q is the branching ratio from the excited state to the lower hyperfine ground state.[10]

The total probability p_{sp} for an incoherent reflection due to these three decay channels is[3]

$$p_{sp}=\Gamma\int_{-\infty}^{\infty}\frac{s}{2}\,dt=\frac{2\Lambda\Gamma}{v_\perp}\,\frac{E_\perp}{\hbar\delta}\,,$$

where $E_\perp$ and $v_\perp$ are the kinetic energy and velocity of the perpendicular motion on entering the evanescent wave.

When the transition leads to the upper, less light-shifted hyperfine state, $|1,n\rangle \rightarrow |2,n-1\rangle$, the atom loses a potential energy of $\Delta E_{\perp} = U_1(\zeta) - U_2(\zeta)$. The mean energy loss per reflection due to this *Sisyphus cooling* effect is

$$\langle \Delta E_{\perp} \rangle = \int_{-\infty}^{\infty} (U_1 - U_2)\Gamma_{12}\, dt = -(1-q)p_{sp} \frac{2}{3} \frac{\delta_{HFS}}{\delta + \delta_{HFS}} E_{\perp}.$$

Every time the induced cooling occurs, $E_{\perp}$ is reduced by a fraction (2/3) $\delta_{HFS}/(\delta+\delta_{HFS})$. The equilibrium temperature for the Sisyphus cooling alone can be determined by equating the mean decrease of energy during an incoherent reflection with the mean heating by spontaneous scattering (taking repumping into account), giving

$$k_B T \approx \frac{2}{q(1-q)} \frac{\delta + \delta_{HFS}}{\delta_{HFS}} E_R , \qquad (1)$$

where $E_R = (\hbar k)^2/2m$ is the recoil energy.

With a time constant that is long compared with the typical time for the reflection process the atom is repumped to the lower ground state, absorbing a mean number of $1/q$ photons in the process. The random recoils of the scattered photons heat the atoms, but the directed momentum transfer by the photons absorbed from the repumping beam leads to a *spontaneous geometric cooling*. For larger temperatures the cooling rates are generally lower than for the Sisyphus mechanism, but both mechanisms contribute significantly to the equilibrium temperature when they are combined. This temperature is comparable with the temperature for the polarization gradient cooling[9] ($k_B T \approx 10 E_R$).

When the transition leads to the lower hyperfine level again, $|1,n\rangle \rightarrow |1,n-1\rangle$, the atomic motion, aside from the photon recoil, is not affected.

When a spontaneous transition leads to an attractive dressed state, the atom will decay back to a repulsive state in about one excited-state lifetime, resulting in weak induced heating. Because of the small transition rate Γ_{13}, induced heating occurs very rarely, with a probability of $p_{13} = (2E_{\perp}/3\hbar\delta)p_{sp}$ per reflection.

We have performed a Monte Carlo simulation for two different trap geometries. For the first geometry, the evanescent wave is formed on the surface of a *conical* hollow and for the second geometry, it is formed on a *pyramidal* hollow in a glass substrate. Between reflections the atoms move ballistically. With random numbers it is determined for each reflection whether a spontaneous emission occurs and to which dressed level it leads. The momentum change resulting from the absorbed and randomly emitted photons is added to the atomic momentum. In the case of a transition $|1,n\rangle \rightarrow |2,n-1\rangle$ the energy $E_{\perp}$ is reduced, depending on the distance at which the transition has occurred, and the repumping cycle is simulated by scattering three photons from the repumping beam 100 μs after the reflection. It is checked for every reflection whether the atom is lost by hitting the surface or bouncing over the rim.

The hollows have a depth of 4 mm and an apex angle of 90°. We used ensembles of 1000 ^{85}Rb atoms with a Gaussian velocity distribution and rms momentum 10 $\hbar k$ at an initial position 1 mm above the cone rim and 1 mm off the axis. The hyperfine splitting between the ground states with $F=3$ and $F=4$ is $\delta_{HFS}/2\pi = 3.0$ GHz, the natural linewidth is $\Gamma/2\pi = 3.0$ MHz, the laser wavelength is $\lambda = 780$ nm, the laser power $P = 500$ mW, and

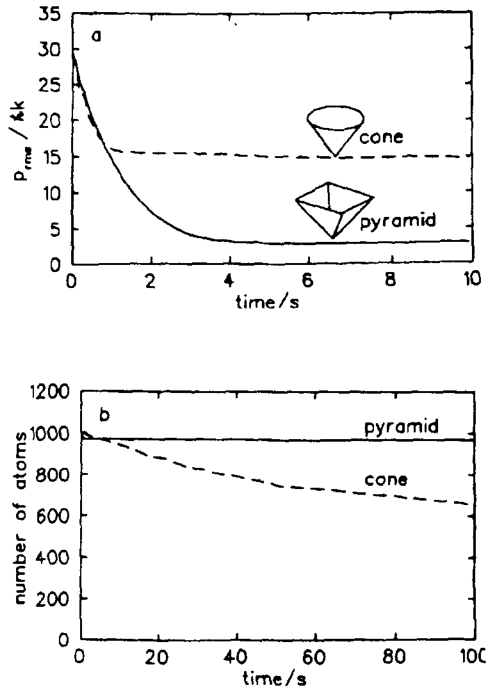

FIG. 3. (a) Root mean square momentum and (b) total number of trapped atoms plotted as a function of the time after release fot the conical and the pyramidal traps. Note the different time scales.

the detuning $\delta/2\pi = 2$ GHz, giving a maximum saturation parameter $s_{max} = 0.02$. The intensity is $I(\rho,\zeta) = I_{max}\exp(-\rho^2/\rho_0^2)\exp(-2\zeta/\Lambda)$, where $2\rho_0 = 4$ mm is the Gaussian laser beam diameter. The decay length is $\Lambda = 0.7\lambda$ for an index of refraction of $n = 1.75$. The repumping beam is directed downward along the symmetry axis of the cone.

The rms momentum of an ensemble of 1000 ^{85}Rb atoms during the first ten seconds after the release is plotted in Fig. 3a for the conical and the pyramidal traps. For the latter, the equilibrium energy agrees with the value found from Eq. (1). It corresponds to $T = 1.5$ μK, but for the conical geometry it is larger by a factor of ~ 20. This stems from the conservation of the angular momentum L_z along the symmetry axis. Even for $E_\perp = 0$ the atoms have a kinetic energy $E_{kin} \geqslant L_z^2/(2m\rho^2)$, rendering both cooling mechanisms ineffective for kinetic energies below $(1/2)(mg^2L_z^2)^{1/3}$.

The number of atoms in the two traps, plotted as a function of time after loading, is shown in Fig. 3b. After small losses during the initial cooling process, virtually no atoms escape from the pyramidal trap, whereas in the conical geometry the final energy is much larger and more atoms can escape. In both geometries one can catch the atoms from standard optical molasses with high efficiency and store them for almost unlimited time.

For ^{39}K and ^{133}Cs we have found similar results for the final temperatures and storage times in both trap geometries.

In conclusion, it is possible to cool atoms to only a few recoil energies in a nearly dark gravitational laser trap. Because the atoms lose potential energy in proportion to their kinetic energy, they accumulate in a very small volume near the bottom of the trap, forming an extremely dense and cold ensemble. In addition, the alkali atoms are held in the lowest ground state, so that losses due to hyperfine changing collisions[11] are strongly suppressed. These properties should make it possible to reach the conditions for a Bose–Einstein condensation.

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