PROPOSALS OF STABLE OPTICAL TRAPS FOR NEUTRAL ATOMS

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Proposals of three dimensional stable optical traps for neutral atoms are presented. Two different laser beam configurations, separately optimized for trapping and cooling, act alternately on the same atomic transition, or simultaneously on two different transitions. Large values are predicted for the ratio optical potential depths over residual kinetic energy.

1. Introduction

This paper presents new proposals of three dimensional optical traps for neutral atoms. Special attention is given to the discussion of the stability of these optical traps in terms of two important parameters (fig. 1), the depth U_0 of the potential well associated with radiative dipole forces [1–4], and the residual total energy E resulting from the competition between diffusion heating and radiative cooling:

$$E = D\tau/M = 3k_B T\,, \qquad (1)$$

where D is the atomic momentum diffusion coefficient [actually the trace of the diffusion tensor] due to the fluctuations of radiative forces [1–4], M the atomic mass, τ the damping time of the atomic velocity due to the cooling force (T is the effective temperature associated with E).

An optical trap can be considered as stable if

$$U_0 \gg k_B T\,, \qquad (2)$$

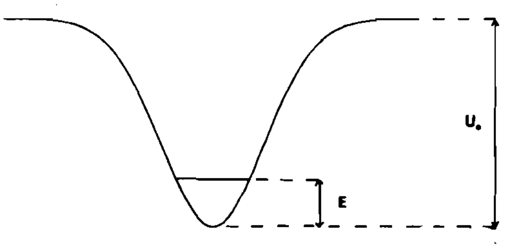

Fig. 1. Important characteristics of an optical trap: potential depth U_0 and residual energy E.

since the escape probability [5] contains the factor $\exp(-U_0/k_B T)$. The problem is therefore to reduce $k_B T$ to the lowest possible value, which is practically of the order of $\hbar\Gamma$ (Γ natural width of the atomic excited state) [6], while achieving the largest possible potential depth U_0, i.e. U_0 much larger than $\hbar\Gamma$.

It is now generally admitted [1] that using a single laser wave does not allow to achieve stable traps, since U_0 and $k_B T$ are at best of the same order. This results from the difficulty of optimizing simultaneously the trapping and cooling efficiencies of a single laser wave. It has been proposed to use two separate waves for cooling and trapping on the same transition [7]. But, in that case, the light-shifts produced by the intense trapping beam strongly perturb the cooling efficiency by introducing a position dependent detuning. The question of the three dimensional stability of such a trap seems to remain open [1,8].

The main idea of the present paper is to decouple the two trapping and cooling functions, either temporally (sect. 4), i.e. by using alternated trapping and cooling phases, or by use of two different atomic transitions sharing no common level (sect. 5). It is then possible to optimize *separately* the two trapping and cooling beams. We discuss in particular in sect. 2 a new laser configuration for trapping which uses two counterpropagating σ^+ and σ^- polarized beams and leads to a deep potential well with a reasonably small diffusion coefficient. The cooling design is discussed in sect. 3.

2. Trapping design

The simplest possible idea is to take a focused travelling gaussian beam tuned below resonance. Dipole forces attract the atom towards the focal zone, but radiation pressure pushes it along the beam. Dipole forces can be predominant, but only in situations leading to a too large momentum diffusion [condition (2) not fulfilled].

The next idea is then to eliminate radiation pressure ‡ by using two counterpropagating waves forming a standing wave [10,11]. But the intensity gradients along the beam are huge (variations over a wavelength λ) and lead to a prohibitive diffusion coefficient D [12], which does not saturate at high intensities or large detunings (i.e. for $U_0 \gg \hbar\Gamma$). Physically, this large value of D is due to the coherent redistribution of photons between the two counterpropagating waves [coherent processes involving absorption in one wave and stimulated emission in the other one [13]]. Such a momentum diffusion can be also interpreted as being due to spontaneous emission which introduces random jumps between two "dressed states" with opposite energy gradients [1,2,14].

Our proposal here is rather to use two counterpropagating σ^+ and σ^- polarized gaussian beams with coincident foci (fig. 2a). The resulting wave has a linear polarization which rotates along the direction of the beam. But the intensity along this direction varies smoothly over a wavelength. The possibility of trapping the atom in the focal zone is the same as for a standing wave, but with a much smaller diffusion coefficient. Because of conservation of angular momentum, redistribution cannot indeed occur between the two waves: absorption of a σ^+ photon cannot be followed by the stimulated emission of a σ^- one (fig. 2b). The redistribution can only occur inside the same wave, so that the contribution of dipole forces to the diffusion coefficient is much smaller than for a standing wave, by a factor of the order of $(1/kw_0)^2$, where w_0 is the beam waist and $k = 2\pi/\lambda$.

‡ Some proposals of optical traps using only radiation pressure [9] are criticized in ref. [8].

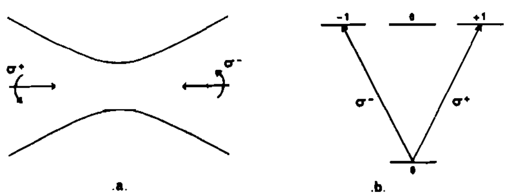

Fig. 2. (a) Trapping configuration: superposition of two focused σ^+ and σ^- counterpropagating waves. (b) Zeeman optical components (for a $J = 0$ to $J = 1$ transition) excited by the σ^+ and σ^- waves.

All the previous qualitative predictions have been confirmed by a quantitative calculation of the potential well and diffusion coefficient for a $J = 0$ to $J = 1$ atomic transition (resolution of the corresponding optical Bloch equations). For a detuning $\delta = \omega_L - \omega_0$ between the laser (ω_L) and atomic (ω_0) frequencies equal to $-100\,\Gamma$, for a saturation parameter

$$s = \frac{\omega_1^2/2}{\delta^2 + (\Gamma^2/4)}, \qquad (3)$$

(where ω_1 is the Rabi frequency) equal to 4, and for a beam waist w_0 equal to 50 λ, one gets a diffusion coefficient due to dipole forces equal to $0.1\,\hbar^2k^2\Gamma$, and a potential depth U_0 equal to $80\,\hbar\Gamma$.

3. Cooling design

In the quasiadiabatic regime $v\tau_R \ll \lambda$ (where v is the velocity and τ_R the radiative lifetime), or equivalently $kv \ll \Gamma$ (Doppler effect small compared to the natural width), the velocity dependence of radiative forces is mainly linear [1] and can be used for damping the atomic motion.

As for trapping, radiation pressure prevents us from using a plane running wave for cooling.

The case of a plane standing wave has been studied in detail [1,15]. For small values of the detuning ($|\delta| < \Gamma/\sqrt{3}$), radiative cooling occurs for $\delta < 0$ as for a travelling wave. For larger detunings, the sign of the velocity dependent force, spatially averaged over a wavelength, changes when the saturation parameter increases. This behaviour remains valid when one takes three perpendicular standing waves with three orthogonal polarizations. A quantitative calculation gives for example for a $J = 0$ to $J = 1$ transition the three dimensional cooling $\boldsymbol{F} = -M\boldsymbol{v}/\tau$ with $\tau = 5M/\hbar k^2$ for $\delta = +4\Gamma$ and $s = 3$. Note that δ has been chosen much smaller than for the trapping configuration in order to avoid large momentum diffusion (here $D = 3.7\,\hbar^2k^2\Gamma$).

Another interesting new possibility is to use the $\sigma^+ - \sigma^-$ configuration of fig. 2a (with a larger beam waist). As for a running wave, cooling (in the direction of the beam) always occurs for $\delta < 0$. The optimum cooling force is found to be $F = -Mv/\tau$ with $\tau = 3M/\hbar k^2$ for $\delta = -\Gamma/2$ and $s = 1$ (the corresponding value of D being $0.25\,\hbar^2k^2\Gamma$). It is however impossible to generalize these results to three orthogonal directions, since one would then reintroduce intensity gradients over a wavelength as in the standing wave case. A simple solution for achieving three dimensional cooling with a single $\sigma^+ - \sigma^-$ laser configuration is to apply it to an asymmetrical trap with three different oscillation frequencies (such a trap can be produced for example by focusing the $\sigma^+ - \sigma^-$ trapping beams with cylindrical lenses). If the cooling beam has equal projections along the three axis of the trap, it damps equally the three components of the atomic velocity (with a three times smaller efficiency) [16–18].

4. Alternating cooling and trapping phases for a $J = 0$ to a $J = 1$ atomic transition

As mentioned in the introduction, our first proposal for achieving the stability condition (2) is to alternate in time cooling and trapping phases, each with a duration T. It is then possible to optimize separately the two functions (as this is done in sections 2 and 3) and to avoid their mutual perturbation ‡.

If the duration T of each phase is large compared to the radiative lifetime τ_R, but small compared to the cooling time τ and to the oscillation period in the potential well, the coefficients appearing in the Fokker-Planck equation describing the atomic motion are the average of the same coefficients corresponding to the cooling and trapping phases:

$$D = \tfrac{1}{2}\,[D_{\text{cool}} + D_{\text{trap}}]\,,$$

$$1/\tau = \tfrac{1}{2}\,[1/\tau_{\text{cool}} + 1/\tau_{\text{trap}}]\,,$$

$$U = \tfrac{1}{2}\,[U_{\text{cool}} + U_{\text{trap}}]\,. \qquad (4)$$

D_{cool} and D_{trap} are of the same order. But $1/\tau_{\text{cool}} \gg 1/\tau_{\text{trap}}$ so that $\tau \simeq 2\tau_{\text{cool}}$ and $U_{0\,\text{trap}} \gg U_{0\,\text{cool}}$ so that $U_0 = U_{0\,\text{trap}}/2$. The stability condition (2) becomes

$$U_{0\,\text{trap}} \gg [2(D_{\text{cool}} + D_{\text{trap}})\,\tau_{\text{cool}}]/3M\,. \qquad (5)$$

Since we have optimized separately $U_{0\,\text{trap}}$ and τ_{cool}, while keeping reasonably small values of D_{cool} and D_{trap}, it follows that stable traps can be achieved [we take "half the best of each function".].

We consider now the two specific examples of Mg and Yb atoms which have a $J = 0$ to $J = 1$ resonance line [^{1}S–^{1}P at 285 nm with $\Gamma = 5 \times 10^8\ \text{s}^{-1}$ for Mg, ^{1}S–^{3}P at 556 nm with $\Gamma = 1.2 \times 10^6\ \text{s}^{-1}$ for Yb]. Using an asymmetrical $\sigma^+ - \sigma^-$ trap and a single $\sigma^+ - \sigma^-$ cooling beam (see end of sect. 3), one gets the following values: for Mg (with a 100 mW trapping laser power † focused on a waist $w_0 = 13\ \mu$m), $U_0 = 40\,\hbar\Gamma$ and $k_BT = 2.5\,\hbar\Gamma$ ($T = 10$ mK); for Yb (1 W on 250 μm), $U_0 = 370\,\hbar\Gamma$ and $k_BT = 2.5\,\hbar\Gamma$ ($T = 24\ \mu$K). Large values of U_0/k_BT are thus achieved (16 for Mg, 150 for Yb).

Finally, we would like to emphasize the versatile character of the alternating scheme. One could for example achieve a more compact spherical trap by alternating trapping phases using $\sigma^+ - \sigma^-$ beams with orthogonal directions. In such a case, the direction of the cooling beam would have also to be alternated. "Black" phases could be also devoted to the observation of unperturbed atoms.

5. Simultaneous cooling and trapping on two different atomic transitions

When a single atomic transition is used, alternating cooling and trapping phases seems the only way to avoid mutual perturbations of the two functions. Another solution is to use simultaneously two different atomic transitions sharing no common level for cooling and trapping (fig. 3).

The 4-level scheme of fig. 3 represents for example a simplified energy diagram for an alkali atom. Levels a and b are then the two hyperfine ground levels, sepa-

‡ The same result would be obtained by leaving the cooling on, all the time, and switching on and off the trapping, since, when the trapping is on, its products light shifts which make the effect of the cooling negligible.

† Entering a linearly polarized beam in an optical cavity containing two quarter wave plates and two focusing lenses, one can produce the laser configuration of fig. 2a, while taking advantage of the power enhancement factor of the cavity. A 100 mW power at 285 nm seems therefore achievable.

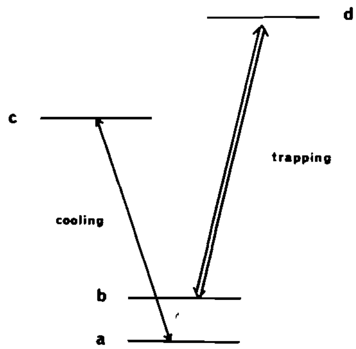

Fig. 3. Four level scheme. Two transitions a–c and b–d are respectively used for cooling and trapping.

rated by the hyperfine splitting S_g. Transition a–c (D_1 line) is used for cooling, with a detuning δ_{cool} and a Rabi frequency $\omega_{1\,cool}$. Transition b–d (D_2 line) is used for trapping (δ_{trap} and $\omega_{1\,trap}$). Because of spontaneous emission processes, c → a, b and d → a, b, the atom interacts randomly and successively with both cooling and trapping beams. The simultaneous presence of the two laser beams prevents atoms from being put in a trap level by optical pumping.

Even if the trapping beam is far from resonance for the a–d transition, it however produces light shifts on level a. If one uses the $\sigma^+ - \sigma^-$ cooling design of sect. 3, which is optimum for $\delta_{cool} = -\Gamma/2$, these light shifts must be kept much smaller than Γ, if one wants an efficient cooling throughout the trap. The standing wave cooling design on the other hand works with larger values of δ and consequently allows larger light shifts of level a. This is why we will prefer here such a scheme.

All these qualitative considerations have been quantitatively confirmed by a numerical resolution of the 16 optical Bloch equations of the problem. Stable trapping is predicted for each alkali atom. Best results are obtained for cesium (λ_{cool} = 894 nm and λ_{trap} = 852 nm with $\Gamma = 3.3 \times 10^7\ s^{-1}$) which has the greatest hyperfine splitting ($S_g = 1740\ \Gamma$) and then allows the most intense trapping beam. For $\delta_{trap} = -250\ \Gamma$, $\omega_{1\,trap} = 200\ \Gamma$ (at the center of the trap), $\delta_{cool} = 10\ \Gamma$ and $\omega_{1\,cool} = 4\ \Gamma$ (averaged over λ), one gets a potential depth $U_0 = 20\,\hbar\Gamma$ with a temperature $k_B T = \hbar\Gamma$, (T = 0.2 mK), i.e. $U_0/k_B T = 20$. We find that the shift of level a due to the trapping beam never exceeds $-5\ \Gamma$ ($< \delta_{cool}$) so that cooling effectively remains efficient on the whole trap.

We finally discuss the validity of our model.

(i) The hyperfine structure of level d ($6P_{3/2}$) in Cs is of the order of 110 Γ. The trap detuning $|\delta_{trap}|$ is larger than this structure, so that if the laser is tuned below the lowest hyperfine level of $6P_{3/2}$, all the four hyperfine levels of d contribute to trapping with the same sign.

(ii) The hyperfine structure of level c ($6P_{1/2}$) in Cs is of the order of 230 Γ. δ_{cool} and $\omega_{1\,cool}$ are much smaller than this structure so that one can choose for c the upper hyperfine level of $6P_{1/2}$ and ignore the other one.

(iii) For each hyperfine level, we have neglected the Zeeman structure. But taking it into account would not change drastically the physical results.

6. Conclusion

We have proposed new laser configurations for trapping and cooling neutral atoms. Stable optical traps have been quantitatively predicted with large values of $U_0/k_B T$ (ranging from 16 to 150). A lower bound for the confinement time can be obtained by multiplying the oscillation period in the trap by $\exp(U_0/k_B T)$ [5]. One finds confinements times larger than one minute in all presented cases. This means that other physical processes (collisions with residual gas for example) will actually limit the trapping time. Finally, the recent developments in the production of slow atomic beams [19,20] seem to provide a possible solution for the problem of loading such traps #.

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For Yb, one would have to use the strong resonance line $^1S-^1P$ at 399 nm, with $\Gamma = 1.8 \times 10^8\ s^{-1}$, for slowing down a thermal beam in a reasonable length.

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