Eur. Phys. J. D **7**, 373–377 (1999)

THE EUROPEAN PHYSICAL JOURNAL D

EDP Sciences

Trapping and cooling cesium atoms in a speckle field

D. Boiron[a], C. Mennerat-Robilliard[b], J.-M. Fournier[c], L. Guidoni[d], C. Salomon, and G. Grynberg

Laboratoire Kastler Brossel, Département de physique de l'École Normale Supérieure, 24 rue Lhomond, 75231 Paris Cedex 05, France

Received 16 December 1998 and Received in final form 16 April 1999

Abstract. We present the results of two experiments where cold cesium atoms are trapped in a speckle field. In the first experiment, a YAG laser creates the speckle pattern and induces a far-detuned dipole potential which is a nearly-conservative potential. Localization of atoms near the intensity maxima of the speckle field is observed. In a second experiment we use two counterpropagating laser beams tuned close to a resonance line of cesium and in the lin $\perp$ lin configuration, one of them being modulated by a holographic diffuser that creates the speckle field. Three-dimensional cooling is observed. Variations of the temperature and of the spatial diffusion coefficient with the size of a speckle grain are presented.

PACS. 32.80.Pj Optical cooling of atoms; trapping

There is presently a considerable interest in the study of disordered media [1]. In condensed matter, the basic concept of electron localization caused by disorder was introduced by Anderson [2]. In optics, the correlations of a speckle field were investigated in great details [3]. Laser cooled atoms [4] provide a physical system which might create a bridge between condensed matter and optics. In this work we use a speckle field to create a sample of cold atoms whose density distribution is closely connected to the intensity distribution of the speckle field. We show that two methods are indeed possible to map the speckle field into an atomic pattern. The first method consists of using the speckle field intensity distribution as a far-detuned dipole trap [5]. Because of the very large detuning between the speckle light field and the cesium resonance, the set of speckle potential wells acts indeed as a non-dissipative potential in which precooled atoms can be trapped. The second method consists of using the speckle field itself to simultaneously cool and trap the atoms. In this case, the beams are tuned close to the atomic resonance and therefore dissipation plays an important role. As shown in a recent theoretical study of this problem [6], strong correlations can be found between the intensity distribution of the speckle field and the atomic density distribution.

In this paper we present experimental results concerning these two methods. In the first experiment, we observe the localization of cesium atoms in an optical potential created by a speckle Nd:YAG beam, the cooling originating from additional lasers tuned to the blue side of the $6S_{1/2}$ $F_g = 3 \rightarrow 6P_{3/2}$ $F_e = 2$ transition [7]. In the second experiment, we show the occurrence of three-dimensional cooling of cesium atoms interacting with two counterpropagating beams having crossed linear polarizations (lin $\perp$ lin configuration [8]) when one of the beams corresponds to a speckle field. In this experiment, the beams are tuned to the red side of the $6S_{1/2}$ $F_g = 4 \rightarrow 6P_{3/2}$ $F_e = 5$ transition. For all experiments, the source of cold atoms is a magneto-optical trap (MOT) [9] with beams tuned on the red side of the $6S_{1/2}$ $F_g = 4 \rightarrow 6P_{3/2}$ $F_e = 5$ transition.

In both experiments, the speckle field is generated with a holographic diffuser. A nearly plane wave impinging on a diffuser is transformed into a speckle field, *i.e.* a field with highly disordered intensity and phase variations. The intensity distribution in a plane perpendicular to the propagation direction is characterized by the parameter d which is the width of the spatial autocorrelation function of the intensity in the transverse plane[1] ($d^2/\lambda_{\rm opt}$ is the typical size in the longitudinal direction). The size d of a speckle grain immediately after the diffuser is estimated to be $d_0 = 10\ \mu$m.

[a] *Permanent address*: Laboratoire Charles Fabry de l'Institut d'Optique, Orsay, France.
e-mail: `denis.boiron@iota.u-psud.fr`
[b] *Present address*: Max Planck Institut für Quantenoptik, Garching, Germany.
[c] *Permanent address*: Rowland Institute for Science, Cambridge, USA.
[d] *Permanent address*: Institut de physique et de chimie des matériaux de Strasbourg, Strasbourg, France.

[1] The average distance between two intensity maxima in the transverse plane is about twice larger.

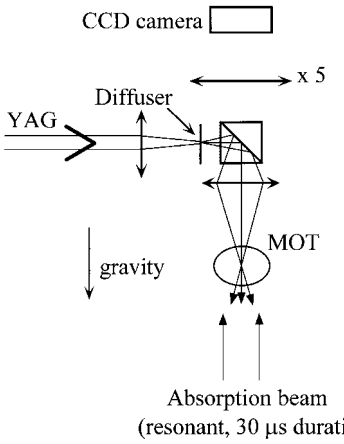

Fig. 1. Scheme of the first experiment. The atoms are trapped in a far-detuned speckle field dipole trap. The speckle field is created by imaging a diffuser by a YAG beam onto the MOT location. A short pulse of resonant light is used to take absorption images on the CCD camera.

1 Trapping in a far-detuned speckle field

In the case of the far-detuned beam, we use the experimental setup described in Figure 1. A Nd:YAG laser beam of wavelength 1.06 μm with a typical power of 2.5 watts illuminates the holographic diffuser. A lens system images the diffuser onto a cloud of cold cesium atoms collected in a vapor cell magneto-optical trap (MOT). The imaging system has a magnification one to one factor (for more details, see [10]). The waist of the YAG beam at the location of the diffuser and of the MOT is 140 μm. Tuning the MOT beams to the blue side of the $6S_{1/2}$ $F_g = 3 \rightarrow 6P_{3/2}$ $F_e = 2$ transition in the absence of any magnetic field produces Sisyphus cooling that brings the cesium atoms at a temperature below 10 μK. Applying simultaneously the speckle field and the cooling beams for 50–100 ms allows to reduce the kinetic energy of the atoms to a sufficiently low value to trap a large number of atoms in the speckle potential.

The spatial distribution of the cesium atoms is observed by an absorption imaging technique [10]. Atoms are quickly optically pumped in $F_g = 4$ (in 100 μs), and a circularly polarized 1 mm diameter probe beam resonant on the $6S_{1/2}$ $F_g = 4 \rightarrow 6P_{3/2}F_e = 5$ cycling transition is sent through the atomic cloud during 30 μs. Its intensity distribution is recorded on a charge-coupled device (CCD) camera with a pixel size of 15 μm (Fig. 1). A X5 microscope objective enlarges the image on the CCD camera so that the image resolution is typically 5 μm. The imaging beam is applied during a short time interval to obtain an instant picture of the atomic spatial distribution without probe-induced modification. We show in Figure 2 several images obtained by illuminating various areas of the holographic diffuser. Clearly the atoms are densely located in very irregular patterns which reflect the random spatial distribution of the speckle light field intensity. The spots have roughly an average width of 12 μm and the mean distance between them is 35 μm. The more populated spots contain a few thousand atoms. This atomic distribution

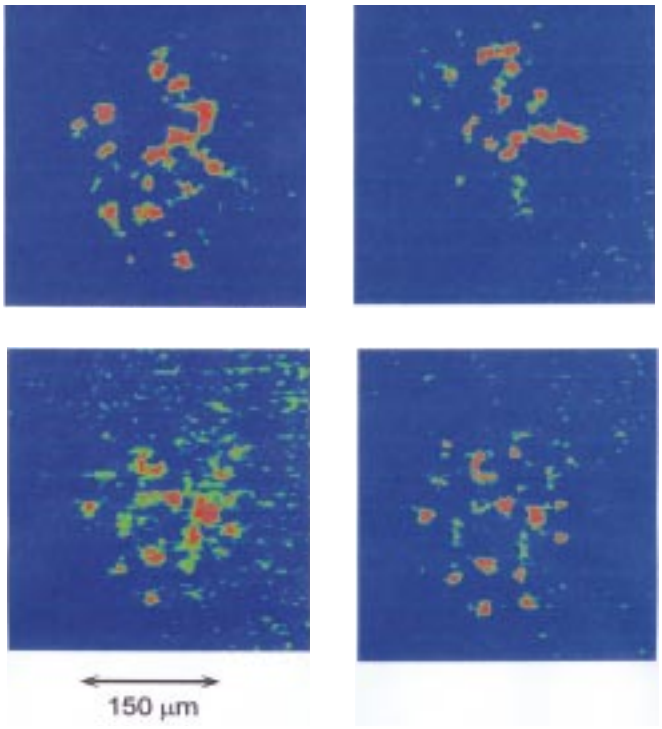

Fig. 2. Images of the atoms trapped in a far-detuned speckle field. Each image is obtained for a different transverse position of the diffuser.

maps the intensity distribution because in a red detuned dipole potential the atoms tend to gather around points of maximum light intensity. However, it should be noticed that the atomic density is not proportional to the field intensity but varies according to a Boltzmann distribution (the dipole potential being proportional to the intensity). In addition, the pictures shown in Figure 2 include some averaging along the longitudinal direction of the atomic cloud which has a dimension equal to 300 μm, a value comparable to the longitudinal size of a speckle grain.

2 Cooling in a nearly resonant speckle field

In the second experiment, two beams having the same frequency ω but crossed linear polarizations are applied onto the cloud of cold atoms once the magnetic field and the beams of the MOT are switched off. One of these beams is transmitted through the holographic diffuser (Fig. 3). This beam configuration resembles the usual 1D lin$\perp$lin configuration [8] but because of the phase and intensity variations in the speckle field, polarization and intensity gradients do exist in the transverse direction[2]. The two counterpropagating beams are horizontal and they are tuned on the red side of the $6S_{1/2}$ $F_g = 4 \rightarrow 6P_{3/2}$ $F_e = 5$ transition (frequency detuning $\Delta = \omega - \omega_0 < 0$ where ω_0 is the atomic resonance frequency). A repumping beam resonant on the $6S_{1/2}$ $F_g = 3 \rightarrow 6P_{3/2}$ $F_e = 4$ transition

[2] A similar behaviour is found in the case of the Talbot lattice [11].

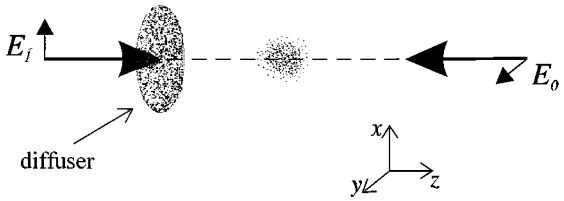

Fig. 3. Scheme of the second experiment. The cold atoms interact with two counterpropagating beams with linear orthogonal polarizations, one of which being transmitted through a diffuser.

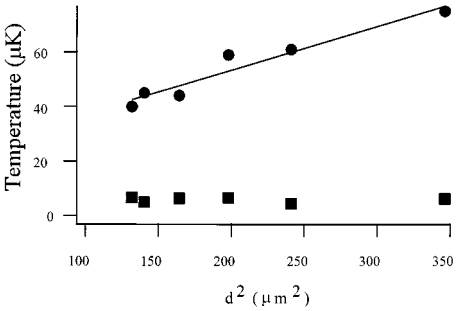

Fig. 4. Variation of the longitudinal (■) and transverse (●) temperatures *versus* the square of the size d of the speckle grains for $\hbar\Delta'_0 = -100E_R$ and $\Delta = -30\Gamma$. As expected from a simple theoretical model, the longitudinal temperature is independent of d in this range of parameters, while the transverse temperature increases linearly with d^2. The line represents a fit of the transverse temperature according to the theoretical law (Eq. (1)).

avoids leakage of the atoms into the $F_g = 3$ hyperfine sublevel. Because of the divergence (3 degrees) of the beam transmitted through the holographic diffuser, the relative intensities of the two counterpropagating beams requires to be adjusted to prevent a unidirectional motion of the atoms that would be generated by a non balanced average radiation pressure. The beam divergence also limits the fluence at the trap location.

The first interesting result of this experiment is that three-dimensional cooling of the cesium atoms is observed in this quasi-1D beam configuration. The kinetic temperature along the Ox vertical direction is measured by a time-of-flight technique using a probe beam located 10 cm below the cold atoms cloud. For the Oz longitudinal direction, we use an imaging time-of-flight technique: after the counterpropagating beams are switched off, the atomic cloud expands freely until the MOT beams are switched on again. They freeze the motion in an optical molasses and an image in the yOz plane is taken in 1 ms. Repeating this sequence for different time delays allows to measure the temperature in both longitudinal and transverse directions, the latter being in agreement with the more precise value obtained with the first method along Ox. With the experimental parameters: average light-shift[3] per beam $\hbar\Delta'_0 = -200E_R$, E_R being the recoil energy, and detuning from resonance $\Delta = -20\Gamma$, $\Gamma/2\pi = 5.3$ MHz being the natural linewidth of the $6P_{3/2}$ level, we find a significant difference between the longitudinal temperature $T_l = 10$ μK and the transverse temperature $T_t = 50$ μK. Similarly, a large difference is found for the thermalization times τ_l and τ_t: τ_l is less than 1 ms but $\tau_t = 35$ ms. The lifetime τ_{at} of the atoms in this speckled molasses is 100 ms. By varying intensity and detuning, τ_t ranges from 20 to 80 ms, a value which becomes comparable to τ_{at}. In this latter case, thermal equilibrium is not reached; the data presented in this paper are restricted to the case $\tau_t < \tau_{at}$.

We have also measured T_l and T_t for several values of the size d of a speckle grain. To vary d the holographic diffuser is moved away from the MOT and the longer the distance L from the atoms, the larger becomes d, the variation being described by: $d^2(\mu m) = d_0^2(\mu m) + 1.27L^2(cm)$ with $d_0 = 10$ μm. This variation has been checked in an independent experiment by directly imaging the speckle field onto a CCD camera. We show in Figure 4 the variation of T_l and T_t *versus* d^2 (the other parameters are $\hbar\Delta'_0 = -100E_R$, $\Delta = -30\Gamma$). We observe that T_l is nearly constant. Its value (5 μK) is similar to the value measured for the same value of Δ' in a standard 1D lin $\perp$ lin configuration with two plane waves [12]. In fact, inside a speckle grain, the polarization gradient along the longitudinal axis is almost identical to the one found in the 1D lin $\perp$ lin configuration, particularly in the neighborhood of the areas where the radiation pressure is balanced. One may deduce from this observation that the atoms are mostly located around such areas. The transverse temperature T_t is much larger and shows a linear variation with d^2. These results are in agreement with the predictions of Horak *et al.* [6]. This results from the very different length scales in the longitudinal and transverse directions. Because the length scale in the transverse direction is d instead of λ along the longitudinal axis, one expects the transverse friction coefficient α_t to be on the order of $\hbar k^2\ (\Delta/\Gamma)(\lambda/d)^2$. The momentum diffusion coefficient D_{dip} associated with the fluctuations of the dipole force is affected by the same reduction factor $(\lambda/d)^2$ and is on the order of $\hbar^2k^2\ \Delta'(\Delta/\Gamma)(\lambda/d)^2$. By contrast, the momentum diffusion coefficient D_{sp} associated with the recoil of a spontaneously emitted photon remains unchanged and is on the order of $\hbar^2k^2\Gamma'$ where $\Gamma' = \Delta'(\Gamma/\Delta)$ is the photon scattering rate. The equilibrium temperature $k_B T_t = (D_{sp} + D_{dip})/\alpha_t$ is thus expected to vary as:

$$k_B T_t/(\hbar\Delta') = a + b(\Gamma/\Delta)^2(d/\lambda)^2 \qquad (1)$$

where a and b are numerical factors on a magnitude order of 1. Applying this law to Figure 4, we find $a = 1$ and $b = 5.4$. These values are in good qualitative agreement with the theoretical model developed for a $1/2 \rightarrow 3/2$ transition [6]. However we do not suggest to apply equation (1) with the experimental values of a and b found from Figure 4 for any value of Δ' and Δ/Γ. In particular,

[3] This quantity is defined for a transition having a Clebsch-Gordan coefficient equal to 1. The light-shift Δ' in the lin $\perp$ lin configuration at a point where the light polarization is circular is $\Delta' = 2\Delta'_0$.

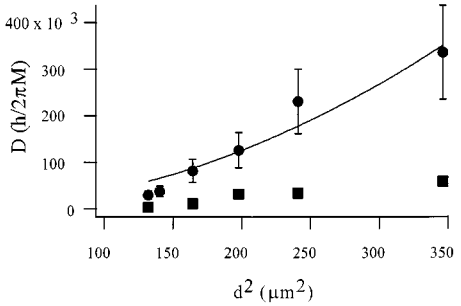

Fig. 5. Variation of the longitudinal (■) and transverse (•) spatial diffusion coefficients *versus* d^2 for $\hbar\Delta_0' = -200E_R$ and $\Delta = -15\Gamma$. The longitudinal spatial diffusion coefficient is $D_1 \sim 0.1$ cm^{2}s^{-1}. The dependence of the longitudinal diffusion coefficient on d is probably due to the jumps of the atoms between two speckle grains. The line represents a fit of the transverse diffusion coefficient according to the theoretical law (Eq. (2)).

for the detuning considered here, it is not possible to consider the $6S_{1/2}$ $F_g = 4 \rightarrow 6P_{3/2}$ $F_e = 5$ as an isolated transition and the effect of the $6S_{1/2}$ $F_g = 4 \rightarrow 6P_{3/2}$ $F_e = 4$ transition is probably significant.

By measuring at different times the spatial dimensions of the cold atomic sample, it is possible to study the expansion law of the atomic cloud [13]. We observe the cloud with a CCD camera and we find that this expansion is diffusive (the square of the cloud width increases linearly with time). We have therefore measured the spatial diffusion coefficients D_1 and D_t in the longitudinal and transverse directions as a function of the parameter d. The experimental results shown in Figure 5 were obtained for $\hbar\Delta_0' = -200E_R$, $\Delta = -15\Gamma$. Here again, we find a significant difference between the longitudinal and the transverse directions. Let us first discuss the longitudinal direction. The slow increase of D_1 with d^2 may originate from jumps between two speckle grains. As mentioned before, there is a domain inside the speckle grain where the radiation pressure is balanced. Once an atom leaves such a position because of fluctuations, it has to travel over a distance on the order of d^2/λ_{opt} (longitudinal size of the speckle grain) along the longitudinal axis before it can find another equilibrium position. Such long flights are probably at the origin of the increase of D_1 with d^2. We now consider D_t. It appears in Figure 5 that D_t increases faster than d^2. This behavior can also be understood by the approach of Horak *et al.* [6]. If we assume that the atoms undergo a Brownian motion in the transverse plane, D_t is connected to the temperature T_t and the friction coefficient α_t through the relation $D_t = k_B T_t/\alpha_t$. Using equation (1), we thus expect:

$$D_t m/\hbar = (\hbar\Gamma'/E_R)(d/\lambda)^2[a' + b'(\Gamma/\Delta)^2(d/\lambda)^2] \quad (2)$$

where a' and b' are numerical factors. Thus, D_t should vary as $(d/\lambda)^2$ for small speckle grains and as $(d/\lambda)^4$ for large speckle grains. In fact, it is possible to fit the experimental points of Figure 5 with equation (2) and we show in Figure 5 the fit obtained for $a' = 3.8$ and $b' = 26$. It can be noticed that $b'/a' = 7$ has the same order of magnitude as $b/a = 5$ but is slightly different. In the cesium case, the model of Horak *et al.* [6] can be used as a guide but it is not sufficient to explain quantitatively our experimental results.

A quantitative comparison in the cesium case requires a numerical simulation. The most reliable theoretical method would be a fully quantum calculation such as a quantum Monte-Carlo simulation [14–16] but this would involve tremendously long computations. A semi-classical approach which is much less time consuming could also be considered. Such an approach can be performed using either the whole set of potential surfaces (9 in the cesium case) in the adiabatic approximation (*i.e.* neglecting non-adiabatic transition between different surfaces) or an effective bipotential as shown in [17]. As long as non-adiabatic transitions are negligible (which is the case for well-localized atoms) these two methods give results in good agreement with the quantum approaches [17]. From this, we can infer that the calculation of the temperature should be in quantitative agreement with the experiments in the parameters range where the atoms are well-localized. For the spatial diffusion coefficient, the influence of the long flights may be poorly described because non-adiabatic transitions are likely to occur along these flights. A quantitative agreement is not expected unless some addition is made in the model to include non-adiabatic transitions. In fact, if one wants only to create a disordered sample of cold cesium atoms with well defined statistical properties, the far-detuned speckle field used as a dipole trap (Sect. 1) looks easier to handle quantitatively.

Finally, we can remark that spatial diffusion is a dominant loss mechanism for the atoms in this disordered optical field. For a laser beam of radius w, the lifetime originating from spatial diffusion is on the order of $\tau = w^2/(2D_t)$. For $w = 5$ mm and $D_t = 2 \times 10^5\, \hbar/m$ we find $\tau = 0.1$ s, in good agreement with the value measured experimentally.

In conclusion, we have presented an experimental study of the properties of cold atoms in a speckle field in two cases. In the first case, the speckle field just creates a spatially disordered but stationary optical potential and we have shown that the atomic pattern follow the field's disorder, the atoms being located near the intensity maxima of the speckle field. In the second case, the speckle field creates a disordered potential but also provides cooling. We consider these experiments as a first exploration in a relatively unexplored domain. In particular the study of atomic localization and transport in the quantum regime seems to be a very promising subject.

The authors wish to thank P. Horak and A. Aradian for helpful discussions. This work was supported by the European TMR network on Quantum Structures FMRX-CT96-0077. Laboratoire Kastler Brossel is an Unité de recherche de l'École Normale Supérieure et de l'Université Pierre et Marie Curie, associée au CNRS.

References

1. See for example *Mesoscopic quantum physics*, Les Houches 1994, Session LXI, edited by E. Akkermans, G. Montambaux, J.-L. Pichard, J. Zinn-Justin (North-Holland, 1995) and references therein.
2. P.W. Anderson, Phys. Rev. **108**, 1492 (1958).
3. J.W. Goodman, *Statistical Optics* (Wiley, New York, 1985).
4. Nobel lectures, S. Chu, C. Cohen-Tannoudji, W.D. Phillips, Rev. Mod. Phys. **70**, 685 (1998).
5. S. Chu, J.E. Bjorkholm, A. Cable, A. Ashkin, Phys. Rev. Lett. **57**, 314 (1986).
6. P. Horak, J.-Y. Courtois, G. Grynberg, Phys. Rev. A **58**, 3953 (1998).
7. D. Boiron, C. Triché, D.R. Meacher, P. Verkerk, G. Grynberg, Phys. Rev. A **52**, R3425 (1995); D. Boiron, A. Michaud, P. Lemonde, Y. Castin, C. Salomon, S. Weyers, K. Szymaniec, L. Cognet, A. Clairon, Phys. Rev. A **53**, R3734 (1996).
8. J. Dalibard, C. Cohen-Tannoudji, J. Opt. Soc. Am. B **6**, 314 (1989); P.J. Ungar, D.S. Weiss, E. Riis, S. Chu, J. Opt. Soc. Am. B **6**, 2058 (1989).
9. E. Raab, M. Prentiss, A. Cable, S. Chu, D. Pritchard, Phys. Rev. Lett. **59**, 2631 (1987).
10. D. Boiron, A. Michaud, J.-M. Fournier, L. Simard, M. Sprenger, G. Grynberg, C. Salomon, Phys. Rev. A **57**, R4106 (1998).
11. C. Mennerat-Robilliard, D. Boiron, J.-M. Fournier, A. Aradian, P. Horak, G. Grynberg, Europhys. Lett. **44**, 442 (1998).
12. M. Gatzke, G. Birkl, P.S. Jessen, A. Kastberg, S.L. Rolston, W.D. Phillips, Phys. Rev. A **55**, R3987 (1997).
13. T.W. Hodapp, C. Gerz, C. Furthlehner, C.I. Westbrook, W.D. Phillips, J. Dalibard, Appl. Phys. B **60**, 135 (1995).
14. P. Marte, R. Dum, R. Taïeb, P.D. Lett, P. Zoller, Phys. Rev. Lett. **71**, 1335 (1993); R. Taïeb, P. Marte, R. Dum, P. Zoller, Phys. Rev. A **47**, 4986 (1993).
15. Y. Castin, K. Mølmer, Phys. Rev. Lett. **74**, 3772 (1995).
16. S. Markenstein, K. Ellinger, P. Zoller, Phys. Rev. A **53**, 3409 (1996).
17. K.I. Petsas, G. Grynberg, J.-Y. Courtois, Eur. Phys. J. D (accepted).