Three-Dimensional Laser Cooling of Helium Beyond the Single-Photon Recoil Limit

J. Lawall, S. Kulin, B. Saubamea, N. Bigelow,* M. Leduc, and C. Cohen-Tannoudji

Collège de France et Laboratoire Kastler Brossel, Ecole Normale Supérieure, 24 rue Lhomond, F-75231 Paris Cedex 05, France

(Received 25 July 1995)

We report the first observation of subrecoil laser cooling in three dimensions, where we use the method of velocity-selective coherent population trapping. We have cooled a cloud of trapped metastable helium atoms to 180 nK, 22 times below the single-photon recoil temperature, with an enhancement in the momentum-space density of 16. We find that the efficiency with which the velocity-selective trap is populated can be augmented by Sisyphus-type frictional forces, while the cooling process is accompanied by the diffusion of atoms to states of very high velocity.

PACS numbers: 32.80.Pj, 42.50.Vk

Cooling an atomic sample to reduce the momentum dispersion δp as much as possible has long been an important scientific goal. During the last ten years, a number of techniques have been proposed and demonstrated, the most important of which use the interaction with light (laser cooling) [1] or elastic collisions (evaporative cooling) [2,3]. In the domain of laser cooling, a natural momentum scale appears: $\hbar k$, the momentum of the laser photon involved in the process, which is also the recoil momentum of an atom absorbing or emitting a single photon. When δp is less than $\hbar k$, the "subrecoil" regime, the coherence length of the atoms in the sample is greater than that of the optical wavelength used to do the cooling. This allows the creation of atomic samples with coherence lengths of the order of several μm, opening up the possibility of studies in which the wave nature of matter is made manifest. Up to now, subrecoil cooling in one and two dimensions has been achieved by two methods: velocity-selective coherent population trapping (VSCPT) [4,5] and Raman cooling [6,7]. Both of these methods depend on diffusion in momentum space, which becomes less and less efficient as the number of dimensions is increased. It is thus a considerable experimental challenge to extend these methods to three dimensions. We report here the first subrecoil laser cooling in 3D, where we use VSCPT, and obtain an atomic coherence length of $\sim$5 μm.

In order to do laser cooling to velocities below the recoil velocity $v_R = \hbar k/m$, it is essential to suppress the random recoil due to spontaneous emission from atoms at very low velocities, while allowing fluorescence cycles for other atoms. The idea of VSCPT is to optically pump atoms into a state that is effectively decoupled by destructive quantum interference from the laser field for sufficiently small center-of-mass velocities. In practice, atoms absorb photons and spontaneously decay, executing a random walk in momentum space, until they fall by chance into a "dark" nonabsorbing state with very small velocity, where they remain. The existence of a velocity-selective nonabsorbing state in any number of dimensions for an atom with a $J_g = 1 \rightarrow J_e = 1$ transition was established by Ol'shanii and Minogin [8]. A simple presentation of this argument is given in Ref. [5]. Briefly, if the laser field is comprised of a superposition of N plane waves with wave vectors $\mathbf{k}_i$ $(i = 1, \ldots, N)$ having the same modulus k, the dark state is given by the same linear superposition of de Broglie waves. More precisely, one finds that atoms are pumped into a coherent superposition of N wave packets with mean momenta $\hbar \mathbf{k}_i$ and with a momentum spread δp, which becomes smaller than $\hbar k$ for sufficiently long interaction times. The efficiency with which the dark state is populated relies on the properties of a random walk in velocity space, with steps corresponding to the absorption of laser photons and subsequent spontaneous emission. Within a volume of velocity space delimited by some $v_{\max}$, the fractional volume within a velocity peak of width δv is proportional to $(\delta v/v_{\max})^D$, where D is the number of dimensions being cooled. Because of the diffusive character of the random walk, the amount of time required to optically pump an atom within a distribution characterized by $v_{\max} \sim v_R$ into a specified velocity interval is thus a rapidly increasing function of D. In fact, in the case of a simple random walk in one or two dimensions, every particle will return to the origin infinitely often, but in three dimensions a nonvanishing fraction of particles will never do so [9]. Fortunately, both theory and experimental work to be described demonstrate that the efficiency with which the nonabsorbing state is populated can be enhanced if the diffusion is supplemented by "frictional" forces providing cooling for velocities somewhat above the single-photon recoil velocity v_R.

To achieve cooling in three dimensions, we have used three pairs of counterpropagating laser beams along orthogonal axes [Fig. 1(a)]. Four beams (1, 2, 3, 4) are in the x-z plane, at 45° to the horizontal, and the two remaining beams (5, 6) are along the y axis. The dotted lines of Fig. 1(a) represent the ballistic trajectories of the wave packets under the influence of gravity, after the VSCPT beams have been applied for a time, which we denote by Θ [10]. The two wave packets (1, 2) associated with laser waves 1 and 2 start with a vertical velocity

 0031-9007/95/75(23)/4194(4)$06.00

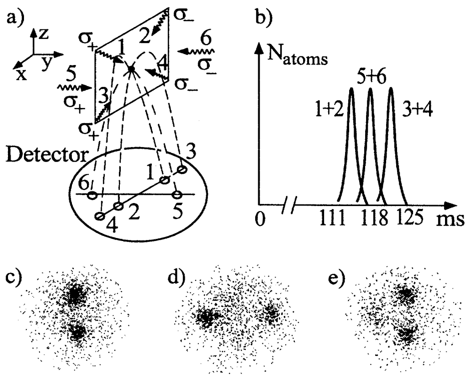

FIG. 1. (a) 3D VSCPT scheme. Under the influence of the six VSCPT beams, the atoms are pumped into a coherent superposition of six wave packets whose centers follow ballistic trajectories to the detector 6.8 cm below. (b) The temporal distribution shows three peaks which, in our experiment, are centered at 111, 118, and 125 ms. (c)–(e) Observed position distributions within temporal windows 107 → 113, 115 → 121, 122 → 128 ms for experimental parameters: $\Omega_R \simeq 0.9\Gamma$, $\delta \simeq +\Gamma$, interaction time $\Theta = 1.5$ ms. The data shown here represent an integration of 150 successive releases of atoms following VSCPT cooling.

component $v_R/\sqrt{2}$ toward the detector and arrive first, at the positions indicated in Fig. 1(a) and at the time indicated by the initial peak in Fig. 1(b). Subsequently, wave packets 5 and 6, and finally 3 and 4, arrive at the positions and times shown. From the widths of the six spots indicated in Fig. 1(a) may be deduced the momentum dispersion δp of each wave packet.

The heart of our experiment is a sample of $\sim 10^4$ metastable helium atoms precooled to $\sim 100\ \mu$K in a magneto-optical trap (MOT) and a detection system capable of simultaneously evaluating all three velocity components of each atom following VSCPT cooling, as described below. After shutting off the trap, the beams for the VSCPT cooling process [Fig. 1(a)], tuned to the $2^3S_1 - 2^3P_1$ transition (1.083 μm), are pulsed on. These beams spatially overlap the trapping beams, and each retroreflected pair has circular σ_+/σ_- polarizations. After VSCPT cooling, the atoms follow ballistic trajectories to a detector of 4 cm diameter based on microchannel plates and a resistive anode. The detector furnishes the individual arrival coordinates (x_i, y_i, t_i) of each detected atom, with a temporal resolution of 5 μs and an estimated spatial resolution of several tens of microns. After each launch of atoms from the trap, the coordinates are sent to a computer for analysis.

In order to spatially resolve the six spots of Fig. 1(a), we use the correlations between the positions and arrival times of the wave packets. The results are shown in Figs. 1(c)–1(e). Using temporal windows of 6 ms centered at 110, 118, and 125 ms, we observe two spots corresponding to the wave packets 1 and 2 [Fig. 1(c)], 5 and 6 [Fig. 1(d)], and 3 and 4 [Fig. 1(e)], respectively. In each case, the width of the spots (proportional to δp) is considerably smaller than the distance separating them (approximately proportional to $2\hbar k$ for spots 5 and 6, and to $\sqrt{2}\,\hbar k$ for pairs of spots 1 and 2, and 3 and 4). This is a clear indication of 3D subrecoil cooling.

To obtain velocity distributions and deduce δv (defined as the half-width at $1/\sqrt{e}$ of the distribution), we make the approximation that the trap is a point source and take advantage of the fact that there is a one-to-one correspondence between detected coordinates (x, y, t) and initial velocity components (v_x, v_y, v_z). We transform our data and find six localized "spheres" in velocity space, each centered at v_R along one of the axes defined by the six laser traveling waves, and each one having a subrecoil velocity distribution. A profile of the velocity distribution along one axis for one of the spheres is shown in Fig. 2(a), accompanied by a fit with a Lorentzian [11]. The laser parameters (detuning $\delta = \omega_L - \omega_0$ and Rabi frequency Ω_R) are $\delta = 1.7\Gamma$ and $\Omega_R = 0.9\Gamma$, and the interaction time is $\Theta = 2.5$ ms. Averaging the squares of the velocity widths over eighteen such profiles taken for the three velocity components of the six wave packets, we find a velocity spread of $\delta v \sim 1.9$ cm/s, 4.8 times below the single-photon recoil velocity v_R. The corresponding atomic coherence length is $4.8 \times 1.083\ \mu\text{m} \approx 5\ \mu$m, and the effective temperature is $T = T_R/4.8^2 = T_R/22 \approx 180$ nK, where T_R is the single-photon recoil temperature defined by $k_B T_R/2 = m v_R^2/2$. We measure the enhancement in momentum-space density by taking the ratio of the density after cooling with VSCPT to that in the MOT. The momentum-space density in the MOT is obtained by counting the number of atoms in a sphere centered at the origin and of radius small (~ 10 cm/s) compared to the

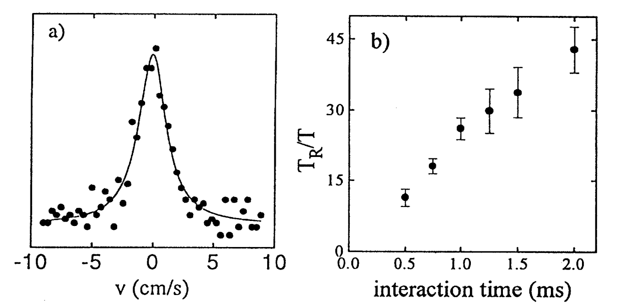

FIG. 2. (a) Profile of the atomic velocity distribution within one wave packet along an axis defined by one of the laser beams, accompanied by a Lorentzian fit. The single-photon recoil velocity $\hbar k/m$ is 92 cm/s. The corresponding curve in the absence of VSCPT would be flat on this scale, and a factor of 16 lower than the peak. Here $\delta = 1.7\Gamma$, $\Omega_R = 0.9\Gamma$, and $\Theta = 2.5$ ms. The units of the vertical axis are arbitrary. (b) Dependence of the temperature on the interaction time Θ, for laser parameters $\delta = \Gamma$, $\Omega_R = 0.7\Gamma$. We have observed temperatures below $T_R/40$.

width of the velocity distribution, and dividing by the volume of the sphere. That obtained after VSCPT cooling is obtained in the same manner but with the small sphere (radius 1.5 cm/s) centered on one of the wave packets. In this way, we find that the enhancement in the momentum-space density in each of the six peaks is 16. Figure 2(b) shows how the temperature evolves with the interaction time Θ for a different set of laser parameters. Here we have averaged over only the (twelve) profiles perpendicular to the laser beams, since at the smallest interaction time the remaining six are not well resolved. As predicted [12,13], the temperature decreases like $1/\Theta$. At the last point on the curve ($T = T_R/45$), however, the momentum-space density is only about a factor of 4 higher than that without VSCPT cooling.

Until now, we have primarily considered the width δv of the velocity distributions. It is also of interest to study the momentum-space density and how it depends on the various laser parameters at our disposal. As in the two-dimensional experiment [5] (see also the paper of J. Lawall *et al.* in Ref. [1]), we observe that the fraction of atoms cooled is much larger with a blue detuning ($\delta > 0$) than on resonance or to the red. This is an indication that Sisyphus cooling accompanies VSCPT for $\delta > 0$ on a $J_g = 1 \longrightarrow J_e = 1$ transition, as predicted by several authors [14,15]. At the same time, one expects that Doppler (radiation pressure) forces, which accelerate for blue detuning, will dominate the Sisyphus force at relatively high velocities.

Our new experimental apparatus allows us to explore not only the distribution of atoms in the six VSCPT wave packets, but also permits, for the first time, a detailed study of the atoms that diffuse to states of higher velocity and are lost. This information is contained in the temporal distribution of atomic arrival times on the detector. In the absence of VSCPT cooling, the time-of-flight distribution is shown in Fig. 3(a). The distribution is peaked at about 77 ms, reflecting both the initial velocity distribution of the trap ($\delta v \sim 45$ cm/s) and the small solid angle ($\Omega = 0.27$ sr) intercepted by the detector. Figure 3(b) shows a temporal distribution accompanying well-resolved VSCPT peaks. Although the three peaks of Fig. 1(b) are not resolved, the center of the distribution arrives at 118 ms, the time taken by an object at rest to fall 6.8 cm. In addition to the ("cold") peak at 118 ms, the figure shows a ("hot") peak at ~ 5 ms, which is indicative of atoms heated in the process. We interpret this peak as consisting of atoms that acquire a sufficiently high speed in the course of their random walk that Doppler forces take over and accelerate them.

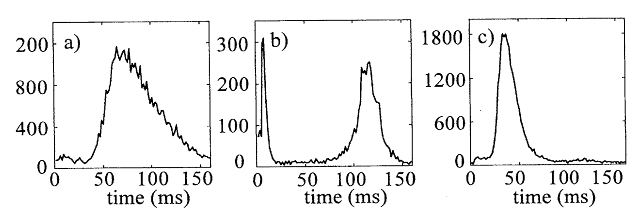

FIG. 3. Time of flight distributions for (a) no VSCPT cooling; (b) blue detuning, $\delta \simeq +\Gamma$; and (c) red detuning, $\delta \simeq -\Gamma$. In each case, $\Omega_R \simeq 0.9\Gamma$ and $\Theta = 0.8$ ms. The vertical scales use the same (arbitrary) units.

A preliminary analysis showed clearly that, at relatively high intensities ($\Omega_R > \Gamma$) and detunings ($\delta > \Gamma$), the six wave packets are not spatially resolved, but the atoms are all in the cold peak of Fig. 3(b); whereas at lower intensities and detunings the wave packets become progressively better resolved, but the hot peak grows at the expense of the cold one. With this in mind, we initiate the VSCPT period with a 100 μs pulse of light on the $J_g = 1 \longrightarrow J_e = 1$ transition with a detuning of $\delta \sim 1.7\Gamma$ and Rabi frequency $\Omega_R \sim 1.7\Gamma$. This compresses the velocity distribution from $\delta v \sim 5v_R$ to $\delta v \sim 1.5v_R$, largely because of the Sisyphus-type forces accompanying VSCPT. This is considerably below the velocity spread normally achievable with Sisyphus cooling; as predicted in Ref. [14], the existence of a nonabsorbing state reduces the momentum diffusion and allows a lower quasiequilibrium temperature for short interaction times. At this point, we commence the subrecoil phase of the process with a smaller intensity and detuning for an interaction time Θ. All the results discussed previously have been obtained in this way.

In order to optimize the enhancement in momentum-space density, it is important to minimize the loss due to Doppler acceleration and simultaneously have strong Sisyphus cooling. To our knowledge a study of VSCPT cooling, including coherent population trapping, Sisyphus, and Doppler forces, has not yet been undertaken. Here, we are able to study the competition between Sisyphus and Doppler forces empirically by switching the sign of the detuning, keeping all other parameters constant. In this case ($\delta < 0$) the Sisyphus force heats at low velocity, but the Doppler force provides friction at higher velocities. As expected, there are many fewer atoms in the VSCPT peaks. If we adopt as a hypothesis that the forces are isotropic, the set of speeds at which Sisyphus heating and Doppler cooling compensate each other forms the surface of a sphere in velocity space. Unlike the case of blue detuning, however, this sphere is stable, and atoms accumulate at this speed. It is in this way that we interpret the time of flight distribution of Fig. 3(c), distinguished from Fig. 3(b) only by the sign of the detuning. From the 40 ms arrival time of the peak one infers that the Sisyphus and Doppler forces cancel for a velocity of 150 cm/s ($\sim 16v_R$). Thus, in the usual case of blue detuning, atoms that execute a random walk to beyond 150 cm/s will be accelerated and lost. We are currently exploring how this "critical" velocity depends on the various laser parameters, with the goal of creating an average frictional force over a much larger part of velocity space. The actual situation is probably more complicated than the model presented here; the forces are most likely not isotropic, and there may, for example, be "channels" in velocity space with less friction than in other directions.

In conclusion, we have demonstrated here that VSCPT is a practical means of achieving subrecoil laser cooling in three dimensions, by means of which we have been able to increase the momentum-space density in a sample of metastable helium by a factor of 16, at a temperature 22 times below the single-photon recoil temperature. We can reduce the temperature still further, but at the expense of momentum-space density. In addition, we have shown empirically that it is not adequate to neglect Doppler forces in a treatment of Sisyphus-enhanced VSCPT. Once the supplementary forces accompanying VSCPT are understood and modeled appropriately, it should be possible to treat the problem theoretically with Lévy flight formalism. This approach [12,16] allows the prediction of the temperature and efficiency of VSCPT in the asymptotic limit where the laser interaction time $\Theta \rightarrow \infty$. The models used in Refs. [12] and [16] are too simple, however, to accurately describe our experimental situation, as they do not provide a loss term for atoms that are accelerated by Doppler forces at high velocities. In a very recent experiment, we have demonstrated the possibility of transferring the atomic population into a *single* wave packet by means of adiabatic passage [17]. We now have a spin-polarized metastable atomic beam source with a de Broglie wavelength of 1.08 μm and a coherence length of $\sim$5 μm, which will be of considerable interest for future work in atom optics.

We thank Alain Aspect, François Bardou, and Maxim Ol'shanii for their contributions. Simone Kulin acknowledges support from the DAAD (Referat 316), and John Lawall a Chateaubriand Fellowship. Laboratoire Kastler Brossel is a Laboratoire de l'ENS et de l'Université Paris VI, associé au CNRS.

---

*Present address: Department of Physics & Astronomy, University of Rochester, Rochester, NY 14627-0171.

[1] See, for example, *Atomic Physics 14*, edited by D.J. Wineland, C.E. Wieman, and S.J. Smith, AIP Conf. Proc. No. 323 (AIP, New York, 1995).

[2] H.F. Hess, Phys. Rev. B **34**, 3476 (1986); J.M. Doyle, J.C. Sandberg, I.A. Yu, C.L. Cesar, D. Kleppner, and T.J. Greytak, Phys. Rev. Lett. **67**, 603 (1991); I.D. Setija, H.G.C. Werij, O.J. Luiten, M.W. Reynolds, T.W. Hijmans, and J.T.M. Walraven, Phys. Rev. Lett. **70**, 2257 (1993).

[3] W. Petrich, M. Anderson, J. Ensher, and E. Cornell, Phys. Rev. Lett. **74**, 3352 (1995); C. Adams, H. Lee, N. Davidson, M. Kasevich, and S. Chu, Phys. Rev. Lett. **74**, 3577 (1995); K. Davis, M.-O. Mewes, M. Joffe, M. Andrews, and W.Ketterle, Phys. Rev. Lett. **74**, 5202 (1995).

[4] A. Aspect, E. Arimondo, R. Kaiser, N. Vansteenkiste, and C. Cohen-Tannoudji, Phys. Rev. Lett. **61**, 826 (1988).

[5] J. Lawall, F. Bardou, B. Saubamea, K. Shimizu, M. Leduc, A. Aspect, and C. Cohen-Tannoudji, Phys. Rev. Lett. **73**, 1915 (1994).

[6] M. Kasevich and S. Chu, Phys. Rev. Lett. **69**, 1741 (1992).

[7] N. Davidson, H.-J. Lee, M. Kasevich, and S. Chu, Phys. Rev. Lett. **72**, 3158 (1994).

[8] M.A. Ol'shanii and V.G. Minogin, in *Light Induced Kinetic Effects on Atoms, Ions and Molecules*, edited by L. Moi *et al.* (ETS Editrice, Pisa, 1991); M. A. Ol'shanii and V.G. Minogin, Opt. Commun. **89**, 393 (1992).

[9] See, for example, D.V. Lindley, *Introduction to Probability and Statistics from a Bayesian Viewpoint, Part I* (Cambridge University Press, London, 1969), pp. 203–210.

[10] In principle, acceleration by gravity during Θ destabilizes the dark state. It can be shown [M.A. Ol'shanii (private communication)] that this effect is negligible as long as the change in velocity $g\Theta$ is less than or of the order of the velocity spread δv achieved by VSCPT during Θ. Since subrecoil laser cooling entails $\delta v < v_R$, Θ is limited to v_R/g; this shows the interest of helium, which has a large v_R (9.2 cm/s).

[11] As discussed in Ref. [5], it is not strictly possible to assign a temperature to VSCPT peaks. Theoretical considerations [12] predict the peaks to have a Lorentzian form. In our work we take δp to be the half-width at $1/\sqrt{e}$ of the momentum distribution, by analogy with the usual thermodynamic situation.

[12] François Bardou, Thèse de doctorat de l'Université Paris XI, 1995 (unpublished).

[13] A. Aspect, E. Arimondo, R. Kaiser, N.Vansteenkiste, and C. Cohen-Tannoudji, J. Opt. Soc. Am. B **6**, 2112 (1989).

[14] M.S. Shahriar, P.R. Hemmer, M.G. Prentiss, P. Marte, J. Mervis, D.P. Katz, N.P. Bigelow, and T. Cai, Phys. Rev. A **48**, R4035 (1993).

[15] P. Marte, R. Dum, R. Taïeb, P. Zoller, M.S. Shahriar, and M. Prentiss, Phys. Rev. A **49**, 4826-4836 (1994); M. Weidemuller, T. Esslinger, M.A. Ol'shanii, A. Hemmerich, and T.W. Hänsch, Europhys. Lett. **27**, 109 (1994).

[16] F. Bardou, J.P. Bouchaud, O. Emile, A. Aspect, and C. Cohen-Tannoudji, Phys. Rev. Lett. **72**, 203 (1994).

[17] P. Marte, P. Zoller, and J.L. Hall, Phys. Rev. A **44**, R4118 (1991).