Physique atomique/*Atomic Physics*

Sub-recoil laser cooling with precooled atoms

François BARDOU, Bruno SAUBAMEA, John LAWALL, Kazuko SHIMIZU, Olivier ÉMILE, Chris WESTBROOK, Alain ASPECT and Claude COHEN-TANNOUDJI

Abstract – This Note describes a new realization of sub-recoil laser cooling by Velocity Selective Coherent Population Trapping (VSCPT). Starting from a cloud of trapped and precooled metastable helium atoms, we have been able to increase the VSCPT interaction time by one order of magnitude over the previous experiment. The resulting temperature T is now 20 times smaller than the recoil temperature T_R associated with the kinetic energy of an atom absorbing or emitting a single photon. The corresponding temperature is 200 nK and the atomic de Broglie wavelength is 4.5 μm.

Refroidissement laser sub-recul avec des atomes prérefroidis

Résumé – *Cette Note décrit une nouvelle génération d'expériences de refroidissement laser sub-recul par Piégeage Cohérent de Population Sélectif en Vitesse (PCPSV). A partir d'un nuage d'atomes d'hélium métastable piégés et prérefroidis, il a été possible d'obtenir un temps d'interaction PCPSV dix fois plus long que dans le schéma expérimental antérieur. La température obtenue* T *est alors 20 fois plus basse que la température de recul* T_R *définie à partir de l'énergie cinétique d'un atome absorbant ou émettant un seul photon. La température correspondante* T *vaut 200 nK, et la longueur d'onde de de Broglie atomique associée vaut 4,5* μ*m.*

Version française abrégée – Dans l'échelle des températures obtenues par refroidissement laser d'atomes (Chu et Wieman, 1989; Arimondo *et al.*, 1992), la température de recul T_R, donnée par $k_B T_R/2 = \hbar^2 k^2/2M$, est une valeur remarquable. Elle correspond à l'énergie cinétique d'un atome de masse M absorbant ou émettant un seul photon d'impulsion $\hbar k$. Dans les processus de refroidissement habituels, les cycles de fluorescence ne s'arrêtent jamais et les reculs aléatoires de l'atome lors des processus d'émission interdisent de descendre au-dessous de T_R (Cohen-Tannoudji *et al.*, 1992). Deux méthodes ont permis de franchir cette limite (Aspect *et al.*, 1988; Kasevich et Chu, 1992). La première, utilisant le piégeage cohérent de population sélectif en vitesses (PCPSV) (Aspect *et al.*, 1988, 1989), combine deux effets : (i) un effet d'interférence quantique qui inhibe l'absorption de lumière pour des atomes se trouvant dans certaines superpositions linéaires d'états caractérisées par une impulsion suffisamment faible $p \simeq 0$ (états « noirs »); (ii) une marche au hasard dans l'espace des impulsions, due aux reculs associés aux photons spontanés, et qui permet aux atomes de diffuser des états $p \neq 0$ vers les états noirs $p \simeq 0$ où ils se retrouvent piégés et où ils s'accumulent.

La figure 1 représente la configuration laser et les états atomiques qui interviennent dans le refroidissement laser PCPSV de l'hélium métastable. La première équation (1) explicite la superposition linéaire $|\psi_{NC}(p)\rangle$ des sous-niveaux fondamentaux non couplée à l'état excité. La superposition orthogonale $|\psi_C(p)\rangle$ est par contre couplée à $|e_0, p\rangle$ par les lasers (même fréquence de Rabi κ), ce qui lui confère une instabilité Γ'_C. Par suite du couplage motionnel $\hbar kp/M$ entre $|\psi_C(p)\rangle$ et $|\psi_{NC}(p)\rangle$ (élément de matrice de l'opérateur énergie cinétique $P^2/2M$ entre ces deux états), l'état $|\psi_{NC}(p)\rangle$ est contaminé par $|\psi_C(p)\rangle$ et acquiert une instabilité caractérisée par le taux de départ $\Gamma'_{NC}(p)$ donné en (2), qui tend vers 0 quand $p \to 0$. L'accumulation des atomes dans les états noirs $|\psi_{NC}(p \simeq 0)\rangle$ se traduit par une distribution d'impulsion présentant deux pics de largeur δp centrés en $\pm \hbar k$. Pour un temps d'interaction Θ, seuls les états $|\psi_{NC}(p)\rangle$ satisfaisant l'équation (3) peuvent être considérés

Note présentée par Claude COHEN-TANNOUDJI.

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comme des pièges parfaits. A partir des équations (2) et (3), on déduit que la température T varie comme l'inverse du temps d'interaction Θ.

Dans la première mise en œuvre expérimentale de la méthode (Aspect *et al.*, 1988), les atomes d'un jet supersonique d'hélium métastable interagissaient avec les lasers PCPSV sur une zone de 3 cm correspondant à un temps d'interaction d'environ 30 μs. Dans la nouvelle expérience décrite ici, la source d'atomes est un nuage d'atomes piégés et prérefroidis à environ 100 μK (soit une vitesse quadratique moyenne de 0,8 m.s^{-1}) dans un piège magnéto-optique (Raab *et al.*, 1987). Après chargement d'un piège d'hélium métastable (Westbrook *et al.*, 1991; Bardou *et al.*, 1992) par un jet ralenti (Phillips et Metcalf, 1982), les atomes sont lâchés et soumis aux lasers PCPSV pendant un temps d'interaction Θ qui peut atteindre 10 ms pour une zone d'interaction de moins de 1 cm. Les atomes tombent ensuite en chute libre sur un détecteur à galettes de micro-canaux de 32 mm de diamètre situé 5 cm plus bas (*fig.* 2). Un écran de phosphore et une caméra CCD synchronisée permettent d'enregistrer les impacts des atomes. Le refroidissement PCPSV requiert de compenser les champs magnétiques parasites qui pourraient recoupler l'état noir $|\psi_{\mathrm{NC}}(p \simeq 0)\rangle$ aux états instables $|\psi_{\mathrm{C}}(p)\rangle$ et $|g_0, p \pm \hbar k\rangle$. Un écran en mu-métal permet de réduire les composantes alternatives à 50 Hz du champ magnétique, les composantes statiques étant compensées par des bobines dont on règle le courant au moyen de signaux d'effet Hanle mécanique (Kaiser *et al.*, 1991).

La figure 3 (a) montre l'image obtenue après avoir moyenné sur 80 lâchers d'atomes. On en déduit le profil de densité spatiale présenté sur la figure 3 (b). Sur ce profil, la distance entre les deux pics correspond à deux fois l'impulsion de recul, soit $2\hbar k$. La demi-largeur des pics permet de calculer la demi-largeur δp à $1/\sqrt{e}$ de la distribution d'impulsion et d'en déduire une température effective à une dimension par $k_{\mathrm{B}}\,\mathrm{T}/2 = (\delta p)^2/2\,\mathrm{M}$. On trouve ici $\mathrm{T} \simeq \mathrm{T_R}/20$ soit 200 nK, ce qui correspond à une longueur d'onde de de Broglie de 4,5 μm.

Plusieurs développements de cette expérience sont envisagés. Une meilleure compensation des champs magnétiques parasites devrait permettre de gagner un ordre de grandeur sur la température à une dimension. Par ailleurs, un tel schéma expérimental est bien adapté aux extensions à deux et trois dimensions du refroidissement PCPSV, proposées dans les références (Aspect *et al.*, 1989; Ol'shanii et Minogin, 1992; Mauri et E. Arimondo, 1991). L'accès à des temps d'interaction longs devrait également permettre d'éprouver les prédictions de la nouvelle approche théorique proposée récemment et fondée sur les vols de Lévy (Bardou *et al.*, 1994). Enfin, l'obtention de paquets d'ondes cohérents, macroscopiquement séparés de 1,3 cm, ouvre des perspectives intéressantes pour l'interférométrie atomique.

INTRODUCTION. – Laser cooling and trapping of atoms is an expanding research field (Chu and Wieman, 1989; Arimondo *et al.*, 1992). Several groups in the world are trying to cool atoms to the lowest temperatures possible and correspondingly to achieve the largest possible de Broglie wavelengths λ_{dB}. In the temperature scale, an important landmark is provided by the single photon recoil temperature $\mathrm{T_R}$, given by $k_{\mathrm{B}}\,\mathrm{T_R}/2 = \hbar^2 k^2/2\,\mathrm{M}$, and corresponding to the recoil kinetic energy $\mathrm{E_R}$ of an atom with mass M absorbing or emitting a single photon with momentum $\hbar k$. Cooling atoms below $\mathrm{T_R}$, *i. e.* with a momentum spread Δp smaller than $\hbar k$, is equivalent to delocalizing the atoms over a de Broglie wavelength λ_{dB} (or, more precisely, over the spatial coherence length $\xi = h/\Delta p$) larger than the laser wavelength $\lambda_{\mathrm{L}} = 2\pi/k$. There are a number of areas which would benefit from sub-recoil cooling, such as atom interferometry, atom optics, atomic clocks and the search for quantum statistical effects.

Until now, only two sub-recoil cooling schemes (Aspect *et al.*, 1988; Kasevich and Chu, 1992) have been proposed and demonstrated (*see* also the proposals described in Pritchard *et al.*, 1987; Wallis and Ertmer, 1989; Mölmer, 1991). The first one (Aspect *et al.*, 1988; Aspect *et al.*, 1989) is based on the physical effect called "Velocity Selective Coherent Population Trapping" (VSCPT). The original demonstration was performed on an atomic beam of metastable helium and led to a one-dimensional temperature of $T_R/2$. The purpose of this Note is to describe the first realization of a new generation of VSCPT experiments, starting from a cloud of trapped and precooled atoms. A preliminary experiment has already allowed us to reach a temperature an order of magnitude lower than that achieved previously. We now get $T \simeq T_R/20$, which in the case of metastable helium corresponds to 200 nK, giving $\lambda_{dB} \simeq 4.5\,\mu$m.

SUB-RECOIL LASER COOLING BY VSCPT. – In most traditional laser cooling schemes, fluorescence cycles never case. It is then impossible to avoid the random recoil due to the spontaneously emitted photons, so that the temperature T always remains larger than the recoil temperature T_R (Cohen-Tannoudji, 1992). This limit is overcome in VSCPT through a combination of two physical effects. First, quantum interference effects prevent atoms from absorbing light if they are in certain linear superpositions of ground state sublevels which have a very small momentum $p \simeq 0$ ("dark" states). Second, for atoms with $p \neq 0$, which scatter photons in random directions, there is a random walk in momentum space which allows some atoms to diffuse from the $p \neq 0$ absorbing states to the $p \simeq 0$ dark states where they remain trapped for a long time and accumulate.

We first recall the principle of VSCPT in a one-dimensional case. Figure 1 shows two counterpropagating laser beams along the Ox axis, with σ^+ and σ^- polarizations, driving respectively the $|g_-, p-\hbar k\rangle \leftrightarrow |e_0, p\rangle$ and the $|g_+, p+\hbar k\rangle \leftrightarrow |e_0, p\rangle$ transitions between the three atomic sublevels e_0, g_-, g_+, of a $J_g = 1 \leftrightarrow J_e = 1$ transition. Here the notation $|e_0, p\rangle$, for example, represents a state where the atom is in the excited sublevel e_0 with momentum p along Ox.

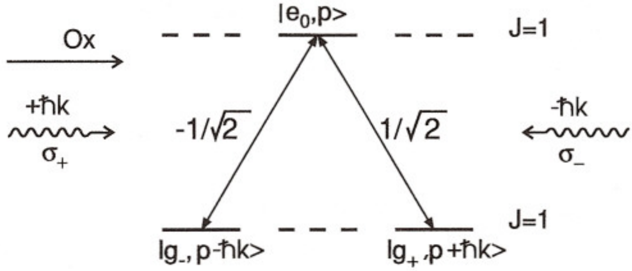


Fig. 1. – *Principle of VSCPT*. Three level Λ configuration on the $2^3\,S_1 - 2^3\,P_1$ transition of ^{4}He. Two ground sublevels $|g_-, p - \hbar k\rangle$ and $|g_+, p + \hbar k\rangle$ are coupled to the same excited sublevel $|e_0, p\rangle$ by two counterpropagating σ^+ and σ^- polarized laser beams at the same frequency. Note the opposite signs of the Clebsch-Gordan coefficients.

Fig. 1. – Principe du refroidissement PCPSV. *Système à trois niveaux en Λ de la transition $2^3\,S_1 \leftrightarrow 2^3\,P_1$ de ^{4}He. Les deux sous-niveaux fondamentaux $|g_-, p - \hbar k\rangle$ et $|g_+, p + \hbar k\rangle$ sont couplés au même état excité $|e_0, p\rangle$ par deux faisceaux laser de même fréquence se propageant dans des directions opposées et polarisés σ_+ et σ_-. Remarquer les signes opposés des coefficients de Clebsch-Gordan.*

Consider the two orthogonal linear combinations of $|g_-, p - \hbar k\rangle$ and $|g_+, p + \hbar k\rangle$

$$(1) \quad \begin{cases} |\psi_{\rm NC}(p)\rangle = \dfrac{1}{\sqrt{2}}\left[|g_-, p - \hbar k\rangle + |g_+, p + \hbar k\rangle\right] \\ |\psi_{\rm C}(p)\rangle = \dfrac{1}{\sqrt{2}}\left[|g_-, p - \hbar k\rangle - |g_+, p + \hbar k\rangle\right]. \end{cases}$$

The state $|\psi_{\rm NC}(p)\rangle$ is not coupled to the excited state because the two transition amplitudes from $|g_-, p - \hbar k\rangle$ to $|e_0, p\rangle$ and from $|g_+, p + \hbar k\rangle$ to $|e_0, p\rangle$ interfere destructively (due to the opposite signs of the Clebsch-Gordan coefficients). By contrast, for $|\psi_{\rm C}(p)\rangle$ the two amplitudes interfere constructively and there is a laser induced coupling between $|\psi_{\rm C}(p)\rangle$ and $|e_0, p\rangle$ which is characterized by the Rabi frequency κ (see *fig.* 2 of ref. Aspect *et al.*, 1989). When $p \neq 0$, the two states $|g_\pm, p \pm \hbar k\rangle$ do not have the same kinetic energy, so that the kinetic energy operator $\mathrm{P}^2/2\,\mathrm{M}$ has a nonzero matrix element between $|\psi_{\rm C}(p)\rangle$ and $|\psi_{\rm NC}(p)\rangle$, equal to $\hbar\, kp/\mathrm{M}$ (motional coupling).

We now show how these various couplings can give rise to a cooling mechanism. Because of the laser coupling to $|e_0, p\rangle$ which has a natural width Γ, $|\psi_{\rm C}(p)\rangle$ is unstable, the departure rate from $|\psi_{\rm C}(p)\rangle$ being equal to $\Gamma'_{\rm C} = 2\,\kappa^2/\Gamma$ at resonance and in the perturbative limit. This instability of $|\psi_{\rm C}(p)\rangle$ is then partially transferred to $|\psi_{\rm NC}(p)\rangle$, because of the motional coupling $\hbar\, kp/\mathrm{M}$. The departure rate out of $|\psi_{\rm NC}(p)\rangle$ is given in the perturbative limit by

$$(2) \quad \Gamma'_{\rm NC}(p) \simeq 2\,\frac{(kp/\mathrm{M})^2}{\kappa^2}\,\Gamma.$$

It thus appears that the states $|\psi_{\rm NC}(p)\rangle$, with $p \neq 0$, are imperfect traps, which become more and more perfect when $p \to 0$. Atoms in $|\psi_{\rm NC}(p)\rangle$ with p sufficiently small will remain trapped, while others will undergo a sequence of fluorescence cycles giving rise to momentum diffusion. They may eventually fall into trapping states (with $p \simeq 0$). The result of VSCPT is thus an accumulation of atoms in states $|\psi_{\rm NC}(p)\rangle$ with $|p| \leqq \delta p$. These states are linear superpositions of two states having momenta $+\hbar k$ and $-\hbar k$, so that the momentum distribution presents a characteristic double peak of half-width δp at eigenvalues $p = \pm\hbar k$. Sub-recoil cooling is achieved when δp is smaller than $\hbar k$.

From the previous analysis, one can qualitatively understand that there is no lower limit to the temperature T which can be expected by such a method. For a total interaction time Θ, only states $|\psi_{\rm NC}(p)\rangle$ such that

$$(3) \quad \Gamma'_{\rm NC}(p)\,\Theta \ll 1$$

can be considered as perfect traps. From equations (2) and (3), one can show (Aspect *et al.*, 1989) that δp scales as $1/\sqrt{\Theta}$, so that the temperature varies as $1/\Theta$ and is limited only by the interaction time.

In the first VSCPT experiment (Aspect *et al.*, 1988), performed with a supersonic atomic beam at 1,100 ms^{-1}, the maximum coherent interaction time was $\Theta \simeq 30\,\mu\mathrm{s} = 300\,\Gamma^{-1}$, corresponding to an interaction region of 3.3 cm. It led to a clear double peak structure with a half-width δp corresponding to a temperature of $\mathrm{T_R}/2$, which showed clearly that the sub-recoil limit could be surpassed.

In fact, VSCPT is capable of yielding much lower temperatures if the coherent interaction time Θ can be increased. It was impossible in the beam experiment to extend the coherent interaction time Θ beyond $300\,\Gamma^{-1}$ because of the difficulty of maintaining the mutual coherence between the laser beams and the g_+ and g_- sublevels over a region larger than 3 cm. This coherence is destroyed by wavefront defects in the laser beams amounting to random phase fluctuations. Coherence is also destroyed by stray magnetic fields which induce a leak from the trapping state. The magnetic field must therefore be compensated over the whole interaction region, which again favors small interaction regions. Increasing the interaction time while keeping a small interaction volume requires the use of a small source of slower atoms, which standard laser cooling techniques are perfectly adapted to provide in the form of a magneto-optical trap.

NEW EXPERIMENTAL SCHEME. – The new experimental scheme is shown in figure 2. We now first precool and accumulate atoms in a magneto-optical trap (Raab *et al.*, 1987) and obtain a sample (Westbrook *et al.*, 1991; Bardou *et al.*, 1992) of 10^5 metastable helium atoms (He*) with an rms velocity of about 0.8 ms^{-1} (100 μK). We then release the atoms and apply the VSCPT laser beams for a controlled interaction time Θ, which can be as large as 10 ms for an interaction region of 1 cm.

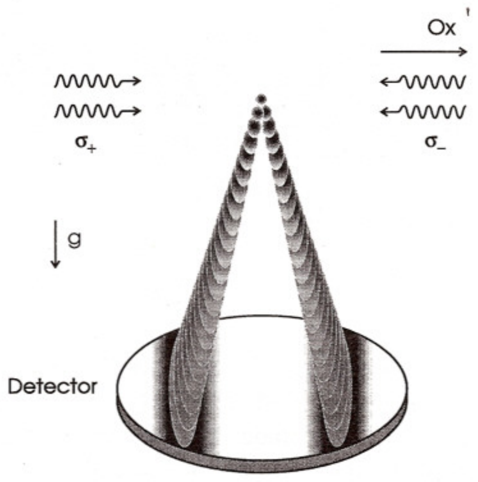


Fig. 2. – *Experimental scheme*. The cloud of trapped atoms at 100 μK is released while the VSCPT beams are applied to cool below the recoil temperature. The atoms then fall freely and their positions are detected 5 cm below on a micro-channel plate of 32 mm diameter. The double band pattern is the signature of the 1D cooling process along Ox which accumulates the atoms into the state $|\psi_{NC}\,(p \simeq 0)\rangle$, a linear superposition of two different momenta.

Fig. 2. – Schéma expérimental. *Les atomes piégés et prérefroidis à 100 μK sont lâchés et soumis aux faisceaux PCPSV qui les refroidissent au-dessous de l'énergie de recul; ils tombent ensuite en chute libre et sont détectés 5 cm plus bas par une galette de micro-canaux de diamètre 32 mm. La structure en double bande est la signature du processus de refroidissement PCPSV à une dimension, qui accumule les atomes dans l'état $|\psi_{NC}\,(p \simeq 0)\rangle$, superposition linéaire d'états ayant deux impulsions différentes.*

The detailed sequence is the following. Starting from a cryogenic beam of He* in the $2^3\,S_1$ state, we first decelerate the atoms by a counterpropagating laser beam tuned on the $2^3S_1 \leftrightarrow 2^3\,P_2$ transition using a Zeeman deceleration technique (Phillips and Metcalf, 1982), and we load the trap which operates on the same transition. The deceleration coils are then turned off for 250 ms, with the trap still in operation, allowing transient magnetic fields to decay. At this point, the trap coils are switched off while the trapping light remains on for an additional 3.5 ms. This allows the magnetic field of the trap coils to decay, while maintaining atoms in an optical molasses. Adjustment of the laser intensity and detuning during these phases allows us to optimize the initial conditions for the VSCPT process.

After turning off the molasses beams, the VSCPT beams are applied on the $2^3\,\mathrm{S}_1 \leftrightarrow 2^3\,\mathrm{P}_1$ transition for an interaction time Θ of 300 μs, during which the atoms move less than 1 mm. As in the previous experiment (Aspect *et al.*, 1988), the two VSCPT laser beams are derived from the same laser, thus providing perfect phase coherence. Atoms with initial velocities directed downwards are detected 5 cm below the trap by an assembly of two microchannel plates of 32 mm diameter (RTC G12–36) and a phosphor screen (RTC P20-KA). Each single detected atom gives rise to a bright spot (diameter 0.8 mm) that can be observed with the naked eye. For quantitative analysis, we use a triggered CCD camera (I2S, IMC500) which can be activated for a duration τ (5 ms in our work) starting at a time t_{fall} (30 to 80 ms) after releasing the atoms. Typically 80 atoms per launch are detected. The whole cycle is repeated 80 times and averaged.

Cooling by VSCPT requires zero magnetic field. Magnetic fields couple the quasi-dark state $|\psi_{\mathrm{NC}}(p)\rangle$ either to $|\psi_{\mathrm{C}}(p)\rangle$ or to $|g_0, p \pm \hbar k)\rangle$, which are unstable because of laser coupling with the excited state. The corresponding additional departure rate out of $|\psi_{\mathrm{NC}}(p)\rangle$ is

$$\Gamma'_{\mathrm{mag}} \simeq 2\,\frac{\Omega_{\mathrm{L}}^2}{\kappa^2}\,\Gamma \tag{4}$$

where Ω_{L} is the Larmor frequency associated with the magnetic coupling between ground state Zeeman sublevels. In order to keep these magnetic losses negligible, we need $\Gamma'_{\mathrm{mag}} \ll \Gamma'_{\mathrm{NC}}(\delta p(\Theta))$, or equivalently

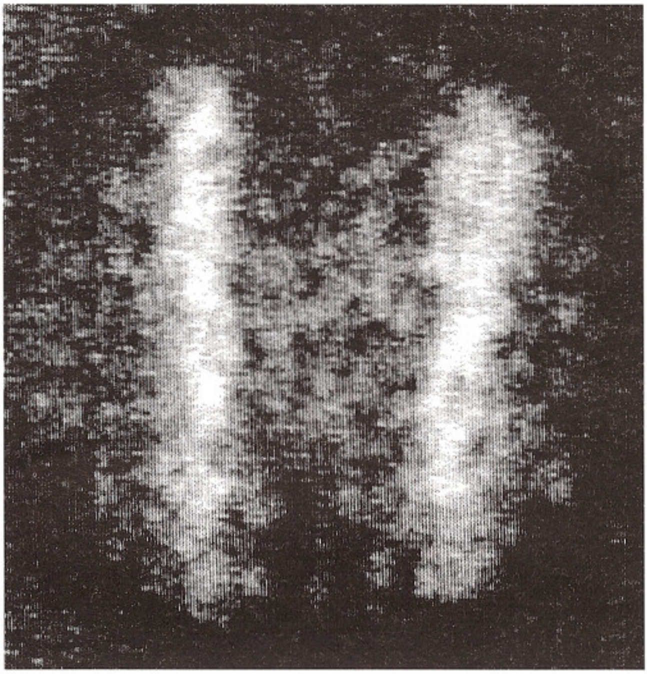
$$\Omega_{\mathrm{L}} \ll \frac{k\,\delta p\,(\Theta)}{\mathrm{M}} \tag{5}$$

To achieve $\delta p \simeq p_{\mathrm{recoil}}/10$, for example, we need a residual magnetic field $\mathrm{B}_{\mathrm{res}} \ll 3\,\mathrm{mG}$.

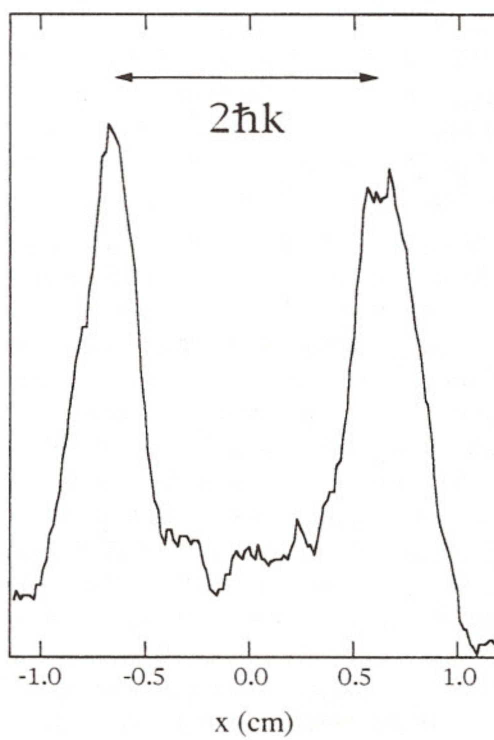
The ac components of the magnetic field at $50\,\mathrm{Hz}\,(\simeq 10\,\mathrm{mG})$ are reduced below 1 mG by the use of a mu-metal shield. The static components are cancelled by compensation coils. This cancellation must be made in the volume and at the time that VSCPT takes place. This is done by an auxiliary step based on the mechanical Hanle effect (Kaiser *et al.*, 1991) performed with the same laser beams as the VSCPT experiment with suitably chosen polarizations. With this technique, the magnetic field is cancelled *in situ* with an accuracy of 0.5 mG. In addition, the decay of the magnetic field can be probed with a temporal resolution of 200 μs. In particular, we have observed a time constant of 700 μs in the decay of the magnetic field of the trap, which might arise from Eddy currents and/or "magnetic viscosity" (Vonsovskii, 1974). This is the reason for waiting 3.5 ms before applying the VSCPT beams.

Experimental results. – The atomic position distribution on the detector is shown in figure 3 a after averaging over 80 single releases from the trap. We clearly see the double band structure which is the signature of VSCPT along the laser axis $\mathrm{O}\,x$. Note that there is no cooling in the other direction. Here the VSCPT interaction time was $\Theta = 300\,\mu\mathrm{s}$ and the Rabi frequency κ was $\kappa \simeq 0.6\,\Gamma$. The detector was exposed for $\tau = 5\,\mathrm{ms}$, starting at a time $t_{\mathrm{fall}} = 73\,\mathrm{ms}$. The corresponding position profile is shown in Figure 3 b.

The observed half-width of each peak is manifestly smaller than the spacing between the peaks which corresponds to $2\,\hbar\,k$. This is a clear indication of cooling below the recoil limit. The intensity at the center of each peak is increased by a factor of 5 when the



(a)



(b)

Fig. 3. – *Experimental results*. Atomic distribution on the detector obtained by VSCPT. (Interaction time $\Theta = 300\,\mu$s, Rabi frequency $\kappa = 0.6\Gamma$.) (a) Image obtained by averaging 80 single shots. The separation of the two bands is 1.3 cm, while the half-width δx_{obs} at $1/\sqrt{e}$ of one band is 1.8 mm. (b) Position density profile corresponding to figure 3 a. The distance between the two peaks corresponds to $2\,\hbar\,k$. From the width of each peak, one estimates that $\mathrm{T} \simeq \mathrm{T_R}/20 \simeq 200\,\mathrm{nK}$.

Fig. 3. – Résultats expérimentaux. *Distribution des impacts atomiques sur le détecteur après refroidissement PCPSV. (Temps d'interaction* $\Theta = 300\,\mu$s, *fréquence de Rabi* $\kappa = 0.6\Gamma$.) *(a) Image obtenue en moyennant 80 lâchers du piège. La séparation des 2 bandes est de 1,3 cm, alors que la demi-largeur à* $1/\sqrt{e}$ *d'une bande est de 1,8 mm. (b) Profil de position mesuré sur la figure 3 a. La distance entre les deux pics correspond à* $2\,\hbar\,k$. *D'après la largeur de chaque pic, on estime* $\mathrm{T} \simeq \mathrm{T_R}/20 \simeq 200\,\mathrm{nK}$.

VSCPT beams are applied, a sign of real cooling (increase of the density in momentum space at $p = 0$).

The quantitative determination of the temperature requires some analysis. Two main factors contribute to the observed position half-width $\delta x_{\rm obs}$. First, there is a kinetic contribution due to the momentum spread along $\mathrm{O}\,x$. Second, there is a contribution δx_0 due to the initial size of the cloud of atoms (half-width 0.5 mm) and to the duration τ of observation. Taking advantage of the velocity spread of the falling atoms on the vertical axis, the time of observation $t_{\rm fall}$ can be varied between 30 ms and 80 ms. Keeping everything else constant, only the kinetic contribution due to δp varies with $t_{\rm fall}$. This contribution can thus be extracted (for $t_{\rm fall} = 50\,\mathrm{ms}$, the contributions of δp and δx_0 to $\delta x_{\rm obs}$ are of the same order) and we find $\delta p/\mathrm{M} = 2\,\mathrm{cm\,s^{-1}}$ (half-width at $1/\sqrt{e}$). Converting this into an effective temperature by $k_{\rm B}\,\mathrm{T}/2 = (\delta p)^2/2\,\mathrm{M}$, we find $\mathrm{T} \simeq \mathrm{T_R}/20 \simeq 200\,\mathrm{nK}$.

Several checks have been performed. First, the double band structure appears in the lin $\perp$ lin configuration, as well as in the $\sigma^+ - \sigma^-$ one, but is not present in the lin $\|$ lin configuration, as expected (Aspect *et al.,* 1989). We have also studied the sensitivity to constant magnetic fields. A magnetic field parallel to the laser axis shifts the Zeeman sub-levels g_- and g_+. The VSCPT scheme can then be generalized by using two counterpropagating lasers whose frequencies differ by twice the Larmor frequency $(2\,\Omega_{\rm L})$. This happens here in a frame moving along $\mathrm{O}\,x$ with a velocity v such that $kv = \Omega_{\rm L}$. The resulting global shift of the two peaks is experimentally observed. On the other hand, when a magnetic field $\mathrm{B}_\perp$ orthogonal to the laser axis is applied, the dark state becomes unstable as explained above, and the double peak structure is smeared when fields $\mathrm{B}_\perp \simeq 5 - 10\,\mathrm{mG}$ are applied.

Finally, we have found that the alignment of the retro-reflection yielding the second VSCPT beam is much less critical than in the beam experiment (Aspect *et al.,* 1988; Vansteenkiste, 1989). Here, the interaction between the atoms and the laser ceases when the two VSCPT beams are simultaneously switched off, rather than when the atoms drift out of the laser beams. This ensures that the interaction with both laser beams stops simultaneously, which is essential.

PROSPECTS. – In conclusion, we have presented a new experimental scheme to achieve VSCPT sub-recoil laser cooling. A preliminary experiment has allowed us to increase the coherent atom-laser interaction time and thus to decrease the temperature by one order of magnitude over the previous demonstration. We have reached a temperature of $\mathrm{T_R}/20$ $(200\,\mathrm{nK})$ for metastable helium corresponding to a de Broglie wavelength $\lambda_{d\mathrm{B}} \simeq 4.5\,\mu\mathrm{m}$. This figure is comparable with the results obtained with the other sub-recoil laser cooling method, *i. e.* $\mathrm{T_{recoil}}/10$ $(100\,\mathrm{nK})$ for Na atoms (Kasevich and Chu, 1992).

We believe that this new experimental scheme for achieving VSCPT has interesting prospects. First, it should allow us to reduce the temperature by at least another order of magnitude in one dimension after more accurate compensation of the stray magnetic fields. Second, this scheme is well adapted to implementing VSCPT in 2 and 3 dimensions, which has been discussed theoretically (Aspect *et al.,* 1989; Ol'shanii and Minogin, 1992; Mauri and Arimondo, 1991). In addition, having access to long interaction times would allow us to test the new theoretical approach to VSCPT based on Lévy flights (Bardou *et al.,* 1994). Finally, VSCPT coherently splits each atom of the initial cloud, yielding two coherent matter wave packets separated by 1.3 cm. This is quite appealing for atomic interferometry and atom optics.

This work was supported by Direction des Recherches, Études et Techniques. One of us (J. L.) acknowledges support from a Chateaubriand Fellowship. We thank Nick Bigelow, Arnaud Landragin and Michèle Leduc for their contributions.

Note remise le 31 janvier 1994, acceptée après révision le 9 mars 1994.

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Collège de France et Laboratoire de Spectroscopie Hertzienne de l'ENS, Laboratoire associé au CNRS et à l'Université Pierre-et-Marie-Curie, 24, rue Lhomond, 75231 Paris Cedex 05, France;

F. B., B. S., J. L., O. E. et C. C.-T. : *Collège de France et Laboratoire de Spectroscopie Hertzienne de l'ENS, Laboratoire associé au CNRS et à l'Université Pierre-et-Marie-Curie, 24, rue Lhomond, 75231 Paris Cedex 05, France;*

K. S. : *Department of applied Physics and Chemistry, The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182, Japon;*

C. W. et A. A. : *Institut d'Optique Théorique et Appliquée,* BP n° 147, *91403 Orsay Cedex, France.*