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Published in:
Physical Review Letters

DOI:
[10.1103/PhysRevLett.78.4185](https://doi.org/10.1103/PhysRevLett.78.4185)

[Link to publication](#)

Citation for published version (APA):

Kulin, S., Saubamea, B., Peik, E., Lawall, J., Hijmans, T. W., Leduc, M., & Cohen-Tannoudji, C. (1997). Coherent manipulation of Atomic Wave Packets by Adiabatic Transfer. *Physical Review Letters*, 78, 4185. DOI: 10.1103/PhysRevLett.78.4185

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Coherent Manipulation of Atomic Wave Packets by Adiabatic Transfer

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(Received 18 February 1997)

We use laser induced adiabatic passage to coherently manipulate the atomic wave packets resulting from subrecoil laser cooling in one, two, and three dimensions by velocity selective coherent population trapping. Using metastable helium atoms, we demonstrate adiabatic transfer into a single wave packet or into two coherent wave packets, while retaining the subrecoil momentum dispersion of the initial wave packets. The efficiency of the transfer is nearly perfect in one and two dimensions, and of the order of 75% in three dimensions. To a large extent, the direction of the momentum and the internal state of the atoms described by each of the final wave packets can be chosen at will. [S0031-9007(97)03292-4]

PACS numbers: 42.50.Vk

In subrecoil laser cooling the atomic momentum spread δp is reduced below $\hbar k$, the photon momentum. The condition $\delta p < \hbar k$ implies that the coherence length of the cooled atoms is larger than the wavelength of the laser that induces the cooling. Two subrecoil cooling methods are known: velocity selective coherent population trapping (VSCPT) [1] and Raman cooling [2]. In VSCPT, a method recently extended to two [3] and three [4] dimensions, atoms are prepared in a coherent superposition of multiple de Broglie wave packets. The momentum spread of each of the wave packets is well below $\hbar k$. It is the purpose of this Letter to show that it is possible to coherently manipulate and control the wave packets resulting from VSCPT. The tool we use is laser induced adiabatic passage [5], which allows one to transfer atoms from one momentum state to another as was pointed out in [6]. Until recently this process had only been demonstrated in one dimension [7]. In this work we show that it can be implemented in two and three dimensions. Preliminary results were presented in [8]. The experiments are carried out with metastable helium in the 2^3S_1 state. The three-dimensional experiments are of particular interest because they can be used to produce an ultraslow, spin polarized atomic beam with subrecoil momentum spread in all directions.

The principle of VSCPT is based on the fact that atoms can be optically pumped into a coherent superposition of ground states with well defined momenta, where they remain indefinitely trapped without absorbing and emitting light. The existence of such perfect trapping states $|\Psi^T(\mathbf{r})\rangle$ for $J_g = 1 \rightarrow J_e = 1$ transitions in one, two, and three dimensions was theoretically predicted and their explicit forms derived in [9]. (See also the presentation given in [3].) For a monochromatic laser field composed of N plane waves, with amplitudes E_j , wave vectors \mathbf{k}_j , and polarizations $\hat{\epsilon}_j$, the complex amplitude is

$$\mathbf{E}(\mathbf{r}) = \sum_{j=1}^N E_j e^{i\mathbf{k}_j \cdot \mathbf{r}} \hat{\epsilon}_j, \quad (1)$$

and the corresponding trapping state, which is not coupled by the laser field to the excited state, is found to be

$$|\Psi^T(\mathbf{r})\rangle \propto \sum_{j=1}^N E_j e^{i\mathbf{k}_j \cdot \mathbf{r}} |\chi_j\rangle, \quad (2)$$

where the normalized internal atomic state $|\chi_j\rangle$ carries the same angular momentum as a photon with polarization $\hat{\epsilon}_j$. For this particular state $|\Psi^T(\mathbf{r})\rangle$, all transition amplitudes connecting a ground state Zeeman sublevel to an excited state Zeeman sublevel interfere destructively, so that an atom in $|\Psi^T(\mathbf{r})\rangle$ cannot be excited by the laser field given in Eq. (1). The state $|\Psi^T(\mathbf{r})\rangle$ is a superposition of momentum eigenstates, each carrying momentum $\hbar\mathbf{k}_j$. In fact, because the wave vectors \mathbf{k}_j are of equal amplitude, $|\Psi^T(\mathbf{r})\rangle$ is an eigenstate of the total Hamiltonian, and thus completely stable. In the presence of the laser field given in Eq. (1), atoms are optically pumped into the trapping state of Eq. (2) through a random walk in momentum space that is velocity selective. The ideal limit of VSCPT would correspond to all atoms being transferred into this state. In practice, a significant fraction is pumped into wave packets with a small momentum dispersion δp around the mean momenta $\hbar\mathbf{k}_j$, δp tending to zero as the interaction time increases.

The key to our approach to wave packet manipulation is the fact that, as seen in Eqs. (1) and (2), the atomic state after VSCPT has the same structure as the laser field itself. Any slow change in the laser field induces a corresponding change of the trapping state. Provided the conditions are such that adiabaticity is guaranteed, the atoms remain decoupled from the laser light during the transfer process and hence do not suffer from heating by spontaneous emission. The final state may be chosen at will; in particular, if at the end of such a change a single laser beam remains, the ensuing atomic state will consist of a single wave packet.

The conditions of the adiabatic passage must be chosen such that the atoms initially in the trapping state are prevented from being coupled to other states, which ultimately would give rise to loss from spontaneous

emission. The simplest case is that of a $J_g = 1 \rightarrow J_e = 1$ system driven by two counterpropagating laser waves with orthogonal linear or circular polarizations, for which the intensity is spatially independent. The adiabaticity criterion for this one-dimensional situation is well known [6]. Defining τ_a as the characteristic time of the adiabatic transfer, the criterion requires that the coupling, which is of the order of \hbar/τ_a , be well below the spacing $\hbar\Omega$ between the eigenstates of the total Hamiltonian ("dressed states"). For the laser intensities we use, Ω is of the order of a few linewidths ($\Gamma \approx 10^7 \text{ s}^{-1}$ for the 2^3P state of He^*), and thus the adiabaticity criterion $\Omega\tau_a \gg 1$ may be satisfied with times of the order of μs . In two and three dimensions the intensity is in general spatially dependent and no rigorous theoretical analysis has been made to date. Because of the periodic spatial variation of the light shifts the energy spectrum has a band structure, and the characteristic energy is no longer $\hbar\Omega$, but rather the recoil energy $E_R = \hbar^2 k^2 / 2m$. For helium the corresponding characteristic time $\hbar/E_R = 3.5 \mu\text{s}$ and it is to be expected that adiabatic passage is feasible on a time scale of tens of microseconds.

The experimental apparatus used to do VSCPT cooling has been described previously [4,10]. A cloud of metastable helium atoms in the 2^3S_1 state is trapped by means of a laser tuned to the 2^3S_1 - 2^3P_2 transition in a magneto-optical trap and cooled to $\sim 100 \mu\text{K}$. Subsequently the magnetic field and the light are switched off and another set of laser beams tuned to the 2^3S_1 - 2^3P_1 transition is turned on for about 1 ms, which cools the atoms by means of VSCPT to $\sim 100 \text{ nK}$. The laser configuration consists of pairs of retroreflected σ_+/σ_- circularly polarized traveling waves. All beams have approximately equal intensities. At this point we either initiate the adiabatic passage to be described below, or perform a reference measurement without adiabatic passage. In both cases the resulting momentum distribution is determined as follows: we shut off the light, and let the atoms follow ballistic trajectories to a detector located 6.5 cm below the interaction region, which records the arrival coordinates (x, y, t) . Knowing the initial coordinates of the atoms, we infer their velocities at the end of VSCPT or adiabatic passage [11].

In order to perform an adiabatic passage we need to control one or more laser beams independently, which we do by means of acousto-optic modulators. In the one- and two-dimensional experiments we slowly, in a characteristic time $\tau_a \approx 10 \mu\text{s}$, turn off all but one of the laser beams at the end of the VSCPT phase. The atoms are thus transferred into the wave packet associated with the remaining laser beam. Great attention was given to the complete extinction of the beams. The final atomic state has a mean velocity of $\hbar k/m \approx 9.2 \text{ cm/s}$ along the direction of the remaining laser beam and an internal state corresponding to the polarization of this beam. Finally, this beam is extinguished $\sim 300 \mu\text{s}$ later in order to avoid subsequent absorption induced by parasitic effects such as stray magnetic fields. In the reference experiments,

without adiabatic passage, care is taken to ensure that all beams are turned off simultaneously (within 300 ns) in order to avoid nonadiabatic losses of atoms.

In Fig. 1 we show the results of a one-dimensional experiment in which we slowly turn off one of two counterpropagating laser beams. The double peaked structure represents the velocity distribution of the atoms after cooling by means of VSCPT, and the single peak is that resulting from adiabatic transfer. We infer an upper limit [11] for the momentum dispersion of the atoms of $\delta p = \hbar k/8$. The width of the momentum distribution after adiabatic transfer has not been changed. In addition, the total number of atoms in the final curve is equal to the total number of atoms in both peaks before the transfer. This is clear evidence that the initial state is indeed a coherent superposition of two states and not a statistical mixture. In contrast, a pure filtering process could never result in more than 50% of the atoms in the final peak. We found that the efficiency of the adiabatic transfer, computed by taking the ratio of the final peak height to the sum of the initial peak heights, monotonically increases with the adiabaticity parameter $\Omega\tau_a$. For the case in which $\Omega\tau_a \approx 10$ the efficiency of the transfer is $\approx 80\%$; in Fig. 1 we have $\Omega\tau_a \approx 60$ and the efficiency is very close to 100%. A detailed quantitative analysis of the dependence of the transfer efficiency on such parameters as τ_a and Ω will be presented elsewhere.

The result of an adiabatic transfer experiment in two dimensions is shown in Fig. 2. First, the two-dimensional velocity distribution [Fig. 2(a)] is prepared using VSCPT with four traveling laser waves. As in the one-dimensional case, after an interaction time of 1 ms, three of the four laser beams are turned off in a characteristic time of $15 \mu\text{s}$. Best adiabatic transfer was obtained by simultaneously raising the power in the fourth beam. The result is shown in Fig. 2(b). The momentum dispersion of the atomic wave packets along the cooling axes is evaluated to be $\delta p \approx \hbar k/6.5$ and no measurable heating is found after the adiabatic passage. The efficiency of the

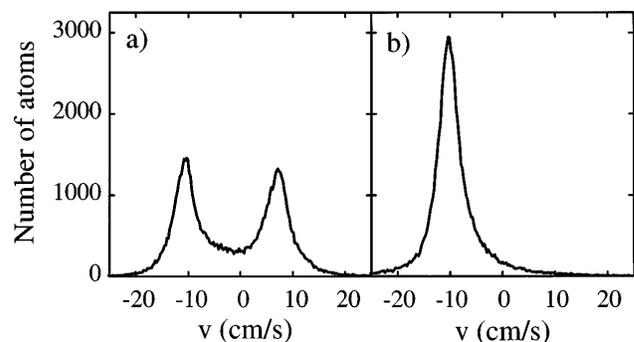


FIG. 1. (a) 1D VSCPT. Velocity distribution of the atoms along the cooling axis after an interaction time $\theta = 1 \text{ ms}$. Here the detuning is $\delta = 0$ and the Rabi frequency in each wave is $\Omega \approx 0.9\Gamma$. (b) The distribution obtained after adiabatic transfer with $\tau_a = 7 \mu\text{s}$. The efficiency of the transfer is of the order of 100%. The recoil velocity is $v_r = 9.2 \text{ cm/s}$.

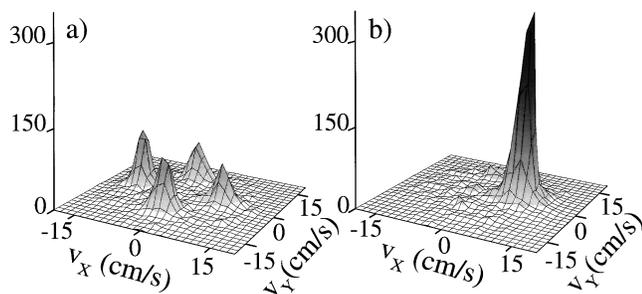


FIG. 2. VSCPT and adiabatic transfer in two dimensions. (a) Subrecoil cooling into four wave packets. (b) Atomic velocity distribution after adiabatic transfer into a single beam with $\tau_a = 15 \mu\text{s}$. Experimental parameters: $\Omega \approx 0.4\Gamma$, $\delta \approx +\Gamma$, and $\theta = 1 \text{ ms}$. The transfer efficiency is $\sim 90\%$. The vertical scales use the same (arbitrary) units.

transfer, calculated as the momentum space density in the center of the single wave packet of Fig. 2(b) divided by the sum of the momentum space densities of the initial four, is found to be of the order of 90%.

The adiabatic transfer experiments in three dimensions were done in two different ways. The first method consists, as in the one- and two-dimensional cases, of reducing the intensity in all but one of the laser beams in order to transfer the atomic population into one of the initially prepared de Broglie wave packets [8]. The second method, which we present here, is more general, since it allows adiabatic transfer into one or several new wave packets that were not part of the initial VSCPT state. Just before the end of a conventional VSCPT cooling phase, using the six-beam geometry described in [4], one or several new laser beams are slowly turned on in a characteristic time $\tau_a^{\text{on}} \approx 20 \mu\text{s}$. After a variable overlap period the intensity of all VSCPT laser beams is slowly reduced in a characteristic time $\tau_a^{\text{off}} \approx 15 \mu\text{s}$. Finally, after another 300 μs , we turn off the additional laser beam(s).

Figure 3 shows the result of the transfer into a single wave packet. The laser configuration used for the cooling in three dimensions is indicated schematically in Fig. 3(a). Four of the six VSCPT beams are in the vertical plane, at a 45° angle to the horizontal, and the two other beams are orthogonal to this plane. The reference experiment, in which VSCPT cooling is not followed by adiabatic passage, leads to an atomic state consisting of six wave packets. In order to resolve them, we use the correlations between their positions and arrival times. In Figs. 3(b), 3(c), 3(d) and the spatial distribution of the atoms in three appropriately chosen time windows are shown. The new laser beam employed in conjunction with the former six beams for the purpose of adiabatic transfer is added in the horizontal plane as indicated in Fig. 3(e). Figures 3(f), 3(g), and 3(h) show the same time windows after adiabatic transfer. As expected, a single spot appears in the central time window at the position associated with the new laser beam, while very few atoms are detected at the positions and times associated with the original six wave packets. By comparing the peak momentum space density in the final wave packet with the sum of the peak momentum space densities in the six wave packets initially prepared by VSCPT, we find the efficiency of the transfer to be of the order of 75%. Adiabatic passage leaves a beam of atoms with a mean velocity of $\hbar k/m = 9.2 \text{ cm/s}$, a momentum dispersion of $\delta p \approx \hbar k/5$, and a momentum-space density a factor of 4.5 ($= 6 \times 75\%$) higher than in any of the six original wave packets. Since δp represents an upper limit to the actual momentum dispersion [11], the corresponding coherence length of the atoms is greater than $h/\delta p \approx 5.4 \mu\text{m}$. The orientation of this atomic beam is related only to the direction of the associated laser wave and is thus arbitrary. Moreover, by choosing the polarization of the additional laser beam, one can prepare the atoms in any desired state of spin except for

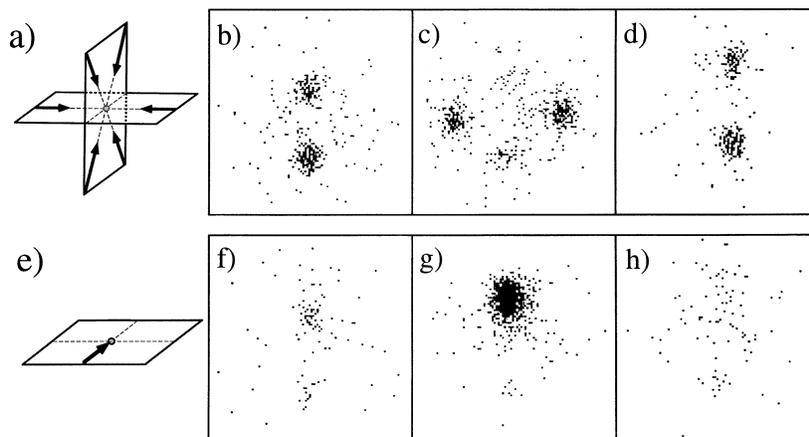


FIG. 3. VSCPT and adiabatic transfer in three dimensions using temporally overlapping laser beams. (a) Laser configuration used for an ordinary 3D cooling experiment. (b)–(d) Observed position distributions within temporal windows 108 \rightarrow 112, 116 \rightarrow 120, 124 \rightarrow 128 ms for experimental parameters $\Omega \approx 0.8\Gamma$, $\delta \approx +\Gamma$, and $\theta = 1 \text{ ms}$. (e) Orientation of the laser beam that induces the transfer. (f)–(h) Position distributions after adiabatic transfer in the same temporal windows as (b)–(d) for $\tau_a^{\text{on}} = 20 \mu\text{s}$ and $\tau_a^{\text{off}} = 15 \mu\text{s}$.

one having a vanishing projection of angular momentum along the propagation direction (the polarization of the laser field is always transverse).

In Fig. 4 we show the result of transfer into two wave packets. While slowly attenuating the six VSCPT beams we progressively turn on two new laser beams in the horizontal plane [Fig. 4(a)] for the purpose of adiabatic transfer. Because of restrictions imposed by the size of the entrance windows, we were limited to angles within 24° between the two beams. The spatial distribution of the atoms in the central time window after adiabatic passage is shown in Fig. 4(b). The velocity profile along a circle of radius $\hbar k/m$ of the atoms is given in Fig. 4(c). The double peak structure indicates that the atoms have been transferred into two different wave packets. According to the isomorphic relation between the atomic waves and the laser field, these wave packets are expected to have the same phase relation as the two laser beams that induce the transfer. This scheme thus provides an atomic beam splitter capable of deflection through a large angle by a single coherent momentum transfer process. The internal state of the atoms in the two final wave packets depends only on the polarization of the two associated laser beams. In particular, if linear polarizations perpendicular to the plane determined by the two laser beams are used, the atoms in the two outgoing wave packets have the same internal state and can interfere. Moreover, the phase between the two wave packets can be controlled. This should prove to be an interesting tool for atom interferometry, especially since the atoms are metastable, which allows detection with very high efficiency and resolution.

In conclusion, we have demonstrated here that laser induced adiabatic passage is a practical means to efficiently transfer atomic population between different momentum states in any number of dimensions. The experiments demonstrate the coherent nature of the initial state produced by VSCPT and lead to a significant increase in momentum space density. We have shown that it is possible to "tailor" the one or multiple outgoing subrecoil atomic

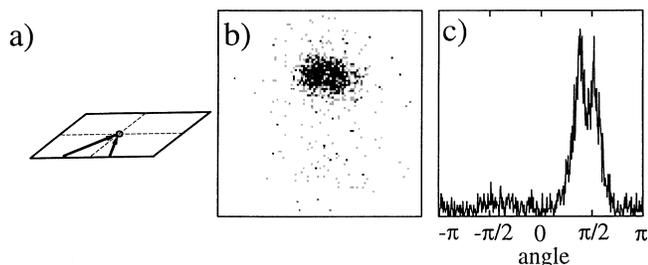


FIG. 4. Three-dimensional VSCPT followed by adiabatic passage into two coherent atomic wave packets. (a) Orientation of the two laser beams that induce the transfer. (b) Position distribution of the atoms in the central time window $116 \rightarrow 120$ ms after the transfer. (c) Velocity distribution along a circle of radius $\hbar k/m$. The experimental parameters are similar to those in Fig. 3.

wave packets, being able to choose their directions and the internal states of the atoms in these wave packets. Apart from being interesting in its own right, this can serve as a fruitful starting point for applications in atom optics.

We thank Yvan Castin, Maxim Ol'shanii, Ernst Rasel, and Nick Bigelow for their contributions. Simone Kulin acknowledges support from the DAAD (Referat 312). Laboratoire Kastler Brossel is a Laboratoire de l'ENS et de L'Université Paris VI, associé au CNRS.

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- [11] As usual, we define the velocity spread $\delta v = \delta p/m$ as the half-width at $1/\sqrt{e}$ of the velocity distribution. When computing the velocities of the atoms, we make the approximation that the width of the atomic distribution that we detect is determined only by the spread in momenta of the atoms at the moment that the laser field is extinguished. We thus ignore all sources of instrumental broadening, including the detector resolution and the initial size of the atomic cloud. The value δv which we determine in this way is then an upper limit to the actual value. We are currently exploring a new method for measuring the actual value of δv free from instrumental broadening.