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Subrecoil Laser Cooling into a Single Wavepacket by Velocity-Selective Coherent Population Trapping Followed by Adiabatic Passage[1]

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Abstract—Laser-induced adiabatic passage has been used to transform the multiple wavepackets resulting from laser cooling by means of velocity-selective coherent population trapping of metastable helium into a single wavepacket. The transfer has been demonstrated in one, two, and three dimensions with efficiencies of 80, 60, and 40%, respectively. In three dimensions, the result is a spin-polarized wavepacket with a coherence length of ~4 μm.

Laser cooling of an atomic sample to a momentum dispersion δp below the momentum $\hbar k$ of the laser photon has been demonstrated in one, two, and three dimensions by means of velocity-selective coherent population trapping [1–4]. This method exploits the fact that on a $J_g = 1 \longrightarrow J_e = 1$ atomic transition, the quantum state with a (three-component vector) wave function isomorphic to the laser field is decoupled from the light (the "dark state") and is, in fact, an eigenfunction of the total Hamiltonian [5]. If the laser field is a superposition of N plane waves, the corresponding atomic state is the same superposition of N plane de Broglie waves. In the course of time, the atomic sample is optically pumped into a set of N coherent wavepackets that approach plane waves in the limit of an infinite laser interaction time. Then, the momentum spread in each of the wavepackets is limited in principle only by the interaction time and may be well below $\hbar k$. The center-of-mass momentum of each of the wavepackets, however, is $\hbar k$ directed along each laser beam, a consequence of the fact that the wave vector of the de Broglie wave is also k (since it is isomorphic to the laser field). Thus, the mean kinetic energy of the sample does not approach zero as the momentum dispersion becomes smaller, and the atomic sample is not in a state of a well-defined momentum. In many cases of practical interest, it would be preferable to have all of the atomic population cooled about the same mean momentum, and in some cases it would be advantageous to cool about $\mathbf{p} = 0$. We have recently demonstrated that these objectives can be fulfilled.

The principle we exploit to put the atomic population into a single wavepacket is adiabatic passage; the atomic sample is prepared in a superposition of N wavepackets, where N is the number of laser beams involved in the cooling, and the laser field is "slowly" changed so as to reduce the intensity in $N - 1$ beams while retaining the intensity in one beam. At any point during this process, the atomic state isomorphic to the laser field is an eigenfunction of the total Hamiltonian, and, if the change in the laser field is made sufficiently slow, the atomic state will adiabatically follow the light field and reduce to a single wavepacket. The idea of transferring atomic population from one state to another by means of adiabatic passage was first demonstrated by the group of Bergmann [6], and the fact that the process could be used to transfer momentum was first pointed out in [7]. Since the population of the excited state can in principle be made arbitrarily small, the method does not suffer from heating by spontaneous emission, and can in fact be thought of as resulting from a stimulated redistribution of photons among various laser beams. Experimental demonstrations of laser-induced momentum transfer by adiabatic passage were first reported in [8, 9]. In the context of laser cooling by means of velocity-selective coherent population trapping (VSCPT) adiabatic momentum transfer has been reported in a one-dimensional experiment with rubidium [10]. Here we demonstrate adiabatic momentum transfer in VSCPT-cooled wavepackets in one, two, and three dimensions in a sample of metastable helium.

The experimental apparatus used to do VSCPT cooling has been described previously [3, 4]. Briefly, a cloud of 10^4–10^5 He* atoms in the 2^3S_1 state are trapped in a magnetooptic trap (MOT) and cooled to ~100 μK by means of a laser tuned to the $J_g = 1 \longrightarrow J_e = 2$ transition. The magnetic field and laser are switched off, and a subsequent pulse of light tuned to the $J_g = 1 \longrightarrow J_e = 1$ transition further cools the atomic sample by means of VSCPT. In D (=1, 2, 3) dimensions, we have used a laser field consisting of D pairs of retroreflected circularly polarized traveling waves with σ_+/σ_- helicities, with a pulse duration of the order of 1 ms. The wavepackets prepared by the VSCPT process follow ballistic trajectories under the influence of gravity to a detector

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located below the MOT, which records the arrival coordinates (x, y, t) of each detected atom with high spatial and temporal resolution. Knowing the point and instant of release, we are able to infer the initial velocity components (v_x, v_y, v_z) of each atom immediately after VSCPT and thus the velocity distribution. As expected, we find 2D wavepackets, each with a momentum dispersion well below that of the laser photons $\hbar k$.

Here we use the same experimental apparatus, but arrange that one of the circularly polarized (σ_+) traveling waves used for VSCPT can be controlled independently of the others by using a separate acoustooptic modulator. The temporal sequence is then the following: during a period Θ of approximately 1 ms, all of the VSCPT beams are turned on with approximately equal intensities. This condition corresponds to a dark state of maximal velocity selectivity, and allows cooling to the lowest possible temperatures during the time Θ. Following this cooling period, the atomic population is transformed adiabatically into a single wavepacket by simultaneously reducing the intensities in all of the VSCPT beams except one during a characteristic time τ_{ap} of the order of 10 μs. The final wavepacket has a center-of-mass momentum of $\hbar k$ along the direction of the remaining laser beam, and an internal state $m_J = +1$ along this direction. The atom must still be decoupled from the field, as is now easily seen by selection rules, although the state is no longer velocity-selective. Finally, the one remaining laser beam is extinguished ~100 μs later, in order to protect against subsequent absorption induced by parasitic effects such as stray magnetic fields.

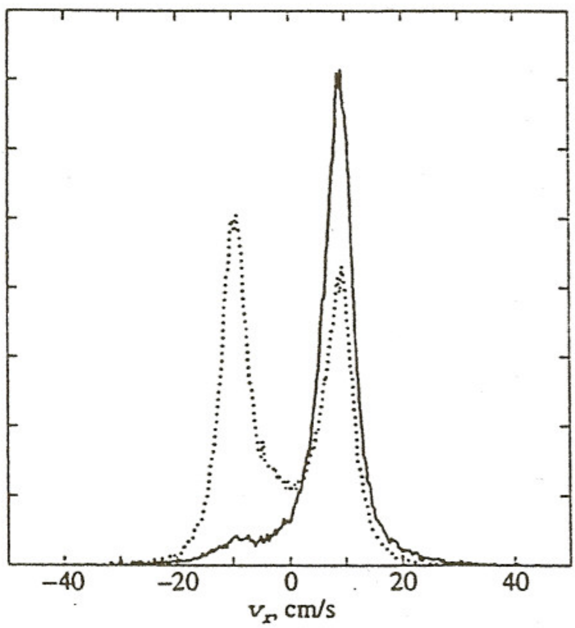

Fig. 1. Results of VSCPT cooling (dotted line) and the same cooling followed by adiabatic passage (solid line). The Rabi frequency is $\Omega = 2.5\Gamma$, and the characteristic time of adiabatic passage is 12 μs. The efficiency of the transfer is of the order of 80%.

For the case of adiabatic passage in a $J_g = 1 \longrightarrow J_e = 1$ system driven by σ_+/σ_- waves in one dimension, the criterion for adiabaticity is well known [7, 11]. Briefly, one finds that the spectrum of the Hamiltonian consists of a level with energy zero (the dark state), and two other states with energies $\pm\hbar\sqrt{\Omega_1^2 + \Omega_2^2}/2$, where $\Omega_{1,2}$ are the Rabi frequencies of the traveling laser waves. Transforming to the basis of eigenstates of the (time-varying) Hamiltonian, the time-dependent unitary transformation is found to induce a coupling of the dark state to the other states with a magnitude of the order of $1/\tau_{ap}$. Adiabaticity requires that this coupling be well below the spacing between energy levels,

$$1/\tau_{ap} \ll \Omega, \tag{1}$$

or

$$\Omega\tau_{ap} \gg 1, \tag{2}$$

where Ω is the Rabi frequency corresponding to the laser left on at the end of the adiabatic passage. Since we typically work with Rabi frequencies of the order of the linewidth Γ (10^7 s^{-1} for He*), condition (2) may be satisfied with times of the order of μs. Nevertheless, there will always be a nonzero amount of coupling out of the dark state, which will give rise to an incoherent loss as the other states are not radiatively stable. Perturbative calculations show that the fractional loss is of the order of

$$\text{Fractional loss} \sim \frac{\Gamma}{\Omega^2\tau_{ap}}, \tag{3}$$

where $1/\Gamma$ is the lifetime of the upper state. In principle, this loss can be made arbitrarily small by working at large laser power and/or long adiabatic passage time.

In two or three dimensions, the energy spectrum is much more complicated due to the band structure arising from the periodic optical potential. The characteristic energy in this case is then not $\hbar\Omega$, but rather the recoil energy $E_R \sim \hbar^2k^2/2M$ [12]. The corresponding time is then $\hbar/E_R \sim 3.5$ μs, so that, although we have not made any detailed calculations, it is to be expected that adiabatic passage is feasible on a time scale of tens of microseconds.

Figure 1 shows results we have obtained in one-dimensional VSCPT cooling. The dotted line shows the familiar twin-peaked structure obtained by VSCPT cooling with approximately equal intensities in the two beams. The interaction time Θ is 2.5 ms, and the Rabi frequency in each wave is $\sim 2.5\Gamma$ with a detuning $\delta = 0$. The measured effective temperature is $T_R/15$, where T_R is the single-photon recoil temperature defined by $kT_R/2 = \hbar^2k^2/2M$. The solid line shows the result of following the VSCPT cooling by a phase in which the intensity in one of the two beams is lowered in a characteristic time of 12 μs in order to adiabatically transfer the population into a single wavepacket. There is no measurable heating, and the efficiency of the adiabatic transfer, computed by taking the ratio of the final peak

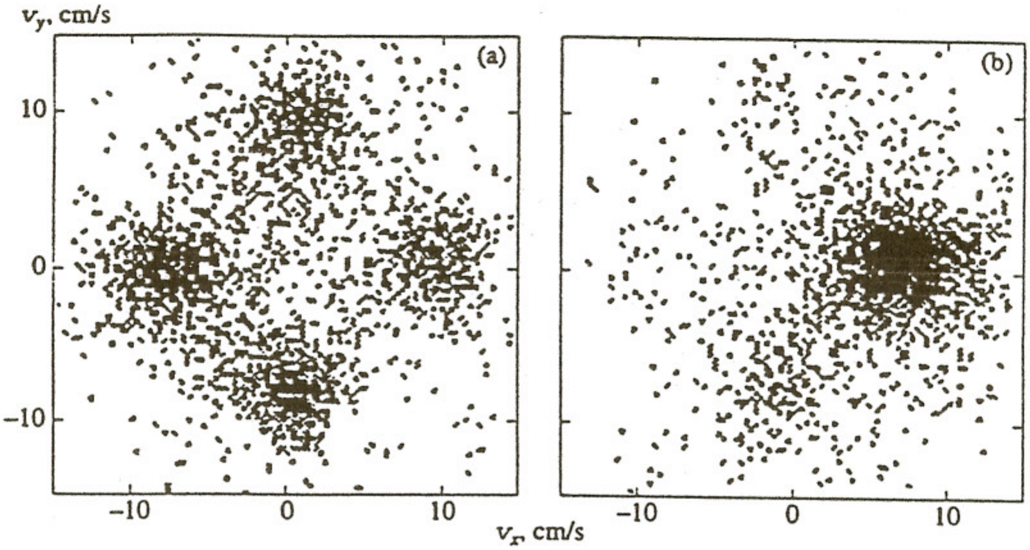

Fig. 2. VSCPT cooling and adiabatic passage in two dimensions: (a) VSCPT cooling into four wavepackets and (b) the result of reducing the intensity in three of the beams in a characteristic time of 6 μs while retaining power in the fourth. The Rabi frequency is $\Omega = 1.5\Gamma$, and the transfer efficiency is of the order of 60%.

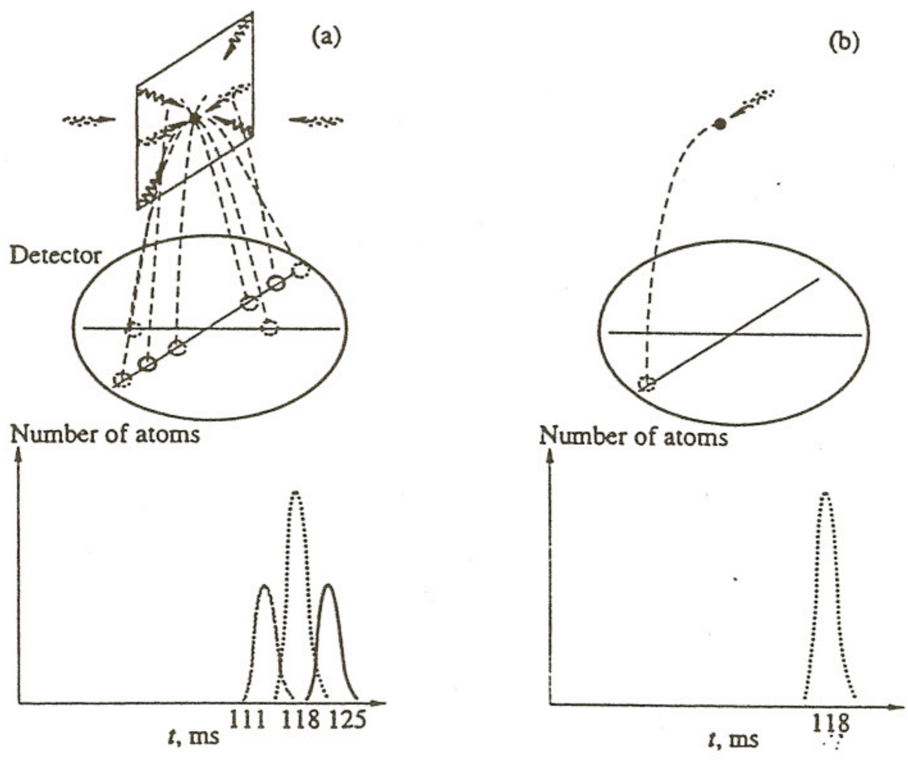

Fig. 3. Experimental scheme for 3D VSCPT cooling followed by adiabatic passage. (a) The system is initially prepared in a set of eight wavepackets which will follow ballistic trajectories to the detector. The time of flight distribution should show three peaks centered at 111, 118, and 125 ms. (b) Following adiabatic passage, the single wavepacket should manifest itself as a single detected spot and a single temporal peak.

height to the sum of the initial peak heights, is ~80%. The small residual in the left-hand peak is expected to be the result of imperfect extinction of the beam that is switched off, or a reflection off of a vacuum window. For the laser parameters used in the adiabatic passage, the product $\Omega\tau_{ap} \approx 300$, so (2) is extremely well satisfied. We have found that the efficiency decreases monotonically with $\Omega\tau_{ap}$, as expected. In fact, however, the loss expected from (3) is of the order of 0.001, so the efficiency of the adiabatic transfer should be expected to be greater than 99%. This matter is currently under investigation.

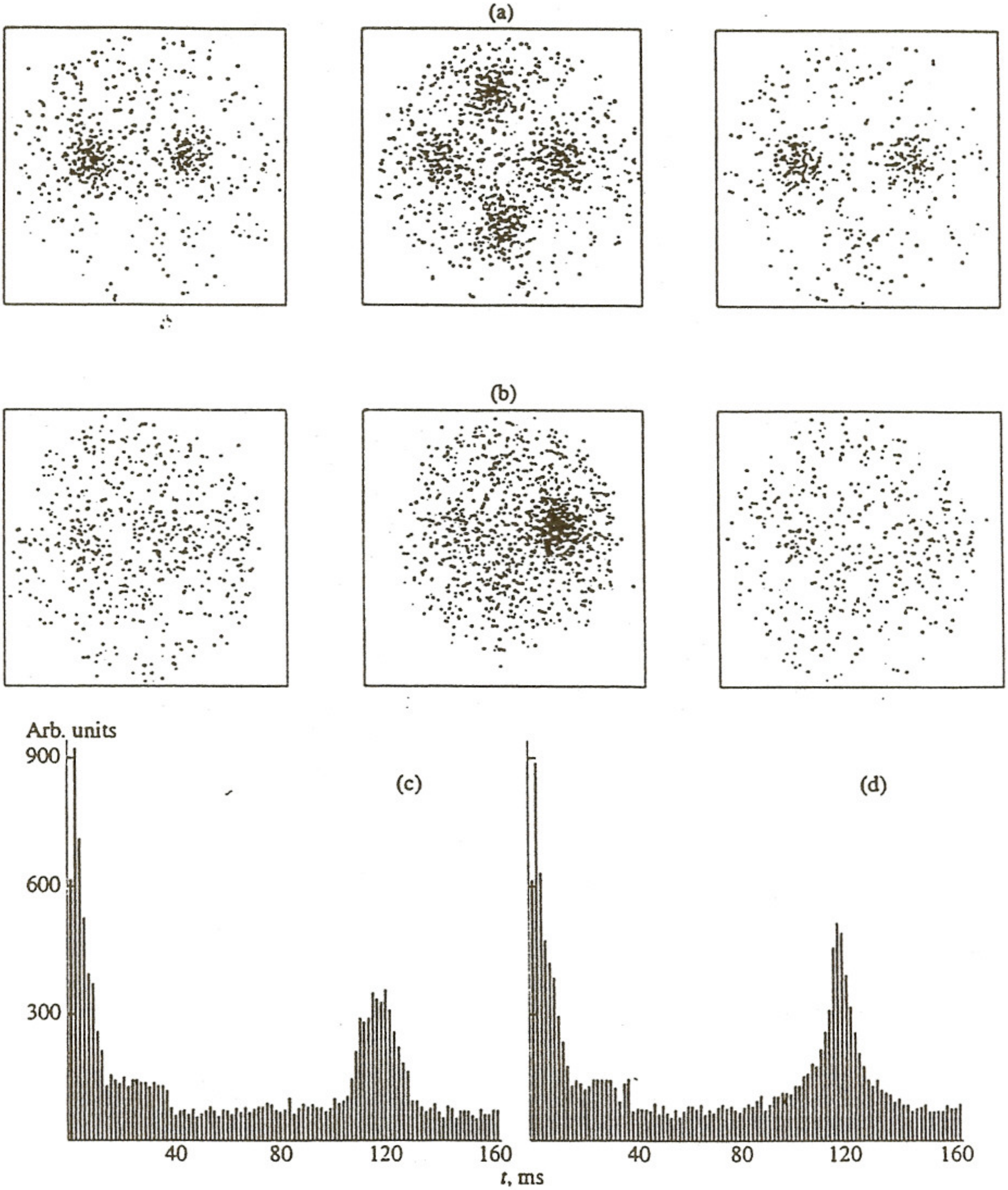

Fig. 4. Correlated spatial/temporal images following VSCPT cooling with eight traveling waves, with $\Omega = \Gamma$ and $\delta = +\Gamma$. The temporal windows used are 107–113 ms, 114–123 ms, and 124–129 ms; (a) eight wavepackets, (b) a single wavepacket created by following the VSCPT cooling by a period of adiabatic passage with a characteristic time of 7 μs, (c) temporal distribution of atomic arrival times corresponding to the situation of eight wavepackets, and (d) temporal distribution for the single wavepacket. Note that the peak at 118 ms is higher and narrower than in the previous case. The origin of the peak of "hot" atoms arriving at very small times is discussed in [4].

An extension of the approach to two-dimensional cooling is shown in Fig. 2. Figure 2a shows gray-scale images of the 2D velocity distribution following VSCPT cooling with four traveling waves, each of which couples with a Rabi frequency $\Omega \approx 1.5\Gamma$ and detuning $\delta \approx +\Gamma$. Here the positive detuning is essential in order to populate the dark state efficiently, as discussed in [3, 4]. After an interaction time $\Theta = 2$ ms, the laser power is reduced in three of the four beams in a characteristic time of 6 μs, with the result shown in Fig. 2b. By mea-

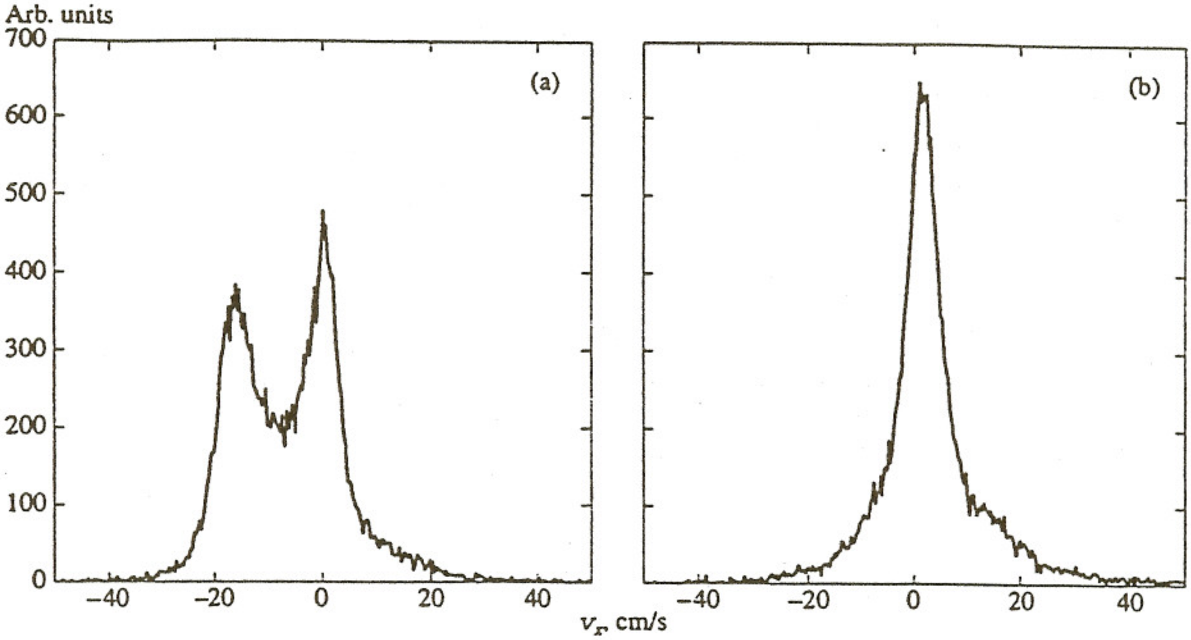

Fig. 5. One-dimensional VSCPT cooling in the presence of a longitudinal magnetic field B (=30 mG) such that $g\mu_B B = \hbar^2k^2/M$: (a) VSCPT cooling produces peaks at 0 and −18 cm/s and (b) the peak at −18 cm/s is brought to 0 by adiabatic passage.

suring the density in the momentum space in the center of the single wavepacket of Fig. 2b, and dividing by the sum of the momentum-space densities of the four wavepackets of Fig. 2a, we find that the efficiency of the adiabatic transfer is of the order of 60%. As in the one-dimensional case, there is no measurable heating.

The generalization of the method to three dimensions is not quite so straightforward, since, with the setup described in [4], all VSCPT pairs are retroreflected and space limitations preclude making any pair of counterpropagating beams independent. Our solution is to add two more beams, independently controllable, and start with *eight* wavepackets and reduce the laser power in seven of the beams following VSCPT cooling. The scheme is shown in Figs. 3a and 3b, along with the spatial and temporal distributions expected on the detector. If VSCPT cooling is not followed by adiabatic passage, the spatial distribution consists of eight packets (in three correlated temporal windows), and the time-of-flight distribution shows three peaks. If the atomic population is put into a single wavepacket, the expected spatial distribution consists of one packet and the temporal distribution is a single peak. Correlated spatial/temporal images detected after VSCPT cooling with eight laser beams, each having $\Omega = \Gamma$ and $\delta \approx +\Gamma$, are shown in Fig. 4a, and the corresponding distributions following an adiabatic passage time of 7 μs are shown in Fig. 4b. It is clear that the population has been effectively transferred into a single wavepacket. Equally striking are the temporal distributions obtained by integrating over the area of the detector. As shown in Fig. 4c, the three peaks shown in Fig. 4a are not resolved, but the peak of slow atoms in Fig. 4d (after adiabatic passage) is considerably narrower and higher than that of Fig. 4c (without adiabatic passage). By transforming our data into momentum space and comparing the momentum density in the final wavepacket to the sum of the momentum-space densities in the eight wavepackets of Fig. 4a, we find that the efficiency of the adiabatic passage is of the order of 40%.

Finally, we note that, by doing VSCPT cooling in a reference frame moving with respect to the lab at a velocity $\hbar k/M$, it is possible to arrange a situation in which one of the wavepackets is *stationary* in the lab frame. In 3-D, for example, this could be done by cooling in the xy-plane with laser beams tuned to some optimal frequency ω, and along the z-axis by independent beams tuned to $\omega \pm \hbar k^2/M$. In this case, one of the wavepackets generated along z would be stationary in the lab frame, and the other would have a velocity $2\hbar k/m$. By following this cooling phase with an adiabatic passage in which the final laser beam is that with frequency $\omega - \hbar k^2/M$, the population would be transferred into a single wavepacket at rest in the lab. Alternatively, in one dimension, the same result can be accomplished by using a static magnetic field along the direction of the laser beam, chosen so that the Zeeman splitting induced between the $m_J = \pm1$ sublevels and the $m_J = 0$ level is equal to the Doppler shift generated by atomic motion at the recoil velocity $\hbar k/M$. In 2^3S_1 helium, this field is 30 mG, and Fig. 5a shows the results of 1D cooling in a field of this magnitude. The peak on the right is centered at $v_x = 0$, and the peak at the left has a velocity component $v_x \approx 18$ cm/s, or $2\hbar k/M$. (The fact that the peak at the left appears smaller is largely an artifact due to the circular shape of the detector.) A subsequent adiabatic passage centers the atomic population at $v_x = 0$, as shown in Fig. 5b.

In summary, we have exploited the velocity selectivity of a symmetric VSCPT laser cooling configuration and followed it with an adiabatic passage into a state that is not velocity-selective but yields a single wavepacket. This is, to our knowledge, the first time that laser-induced adiabatic momentum transfer has been demonstrated in more than one dimension. It is important to note that this transformation of two, four, or eight wavepackets into a single wavepacket is possible only because of the initial coherence between the wavepackets; it would not have been possible with a statistical mixture. A number of important questions remain to be studied. In particular, it is clear from the one-dimensional work that the efficiency we observe is below that expected; thus we hope to be able to identify the reason for the relatively low efficiency we observe and improve on it. In two and three dimensions, the theoretical situation is less clear, but it may be possible to increase the transfer efficiency in these cases as well. In fact, it may turn out that reducing the intensity in $N-1$ beams simultaneously is not the best way to effect the adiabatic passage; it may be better, for example, to reduce the intensities pairwise. A theoretical investigation of the band structure should offer some insight. In addition, it may be preferable to raise the laser power in the beam that is not extinguished as the power in the other(s) is slowly reduced.

At present, the adiabatic passage in 3D leaves us with a beam of atoms with a mean momentum of $\hbar k$, corresponding to a velocity of 9.2 cm/s, and a momentum dispersion of the order of 2 cm/s. It would be a straightforward matter, by introducing additional laser frequencies as described above, to put the center-of-mass velocity of the sample at rest. The ultraslow atomic beam already demonstrated, however, is very interesting in its own right.

The de Broglie wavelength is 1.08 μm, the atomic coherence length is ~4μm, and the beam is spin-polarized. In addition, it is metastable, which allows detection with extremely high resolution and efficiency. This should prove to be an interesting tool in the field of atom optics.

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