Ramsey-Type Subrecoil Cooling

Frank Sander, Thibaut Devolder, Tilman Esslinger, and Theodor W. Hänsch
Sektion Physik, Ludwig-Maximilians-Universität, Schellingstraße 4/III, D-80799 Munich, Germany
and Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany
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We experimentally study the motion of atoms interacting with a periodically pulsed near resonant standing wave with a polarization gradient. The atoms are cooled to a comblike momentum distribution. The peaks have widths of $\approx 0.3\hbar k$ and a spacing which is an integer multiple of the recoil momentum $\hbar k$. The atomic population is accumulated in ground states which periodically evolve to dark states each time the standing wave is switched on. These light pulse synchronously recurring dark states exist for discrete pulse frequencies, even if no stationary dark states are present. [S0031-9007(97)03250-X]

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Ultracold atoms form an ideal system to study the evolution of matter waves. The cold atoms have a large spatial coherence and can be manipulated by atom-light interaction. Using laser light, motional quantum states of atoms can be precisely prepared and observed. Very recently, Bloch oscillations [1] and the Wannier-Stark ladder [2] have been demonstrated in fascinating experiments, where laser cooled atoms interacted with an accelerating standing wave potential. A similar system has been used to study the relation between quantum evolution and the underlying classical dynamics [3]. These experiments were performed in a regime where dissipation due to spontaneous emission was negligible.

In this work we study the evolution of atomic matter waves interacting with a periodically pulsed standing wave in the presence of dissipation. We prepare atoms via spontaneous emission in nonstationary quantum states, which are superpositions of different momentum eigenstates. We monitor their evolution and observe revivals of states which are decoupled from the light field by varying the time between successive pulses. The periodic interaction with the standing wave leads to an accumulation of the atoms in a comblike momentum distribution with peaks narrower than the recoil momentum of a single photon. Our scheme can thus be regarded as a new approach to subrecoil cooling. In velocity selective coherent population trapping (VSCPT) [4] and Raman cooling [5] the velocity selection is achieved during the interaction with either a continuous light field or with a velocity selective Raman pulse. For both techniques a long interaction time with the light field results in narrow momentum distributions. In our scheme the kinetic evolution of the atoms between successive pulses leads to the selection of sharply defined velocity classes. This is similar to Ramsey spectroscopy [6], where the energy difference between atomic states is determined using two or more separated interaction regions instead of a single large one.

To understand the interaction of the atoms with the pulsed standing wave let us recall the concept of dark states. Consider an atomic transition which has an integer total angular momentum F both in the ground and excited state manifolds. If this transition is driven with polarized light, there is one ground state of the $2F + 1$ ground states which is not coupled to the excited state manifold [7]. This state is called a dark state and it can be populated by optical pumping.

If the atom interacts with a continuous one dimensional standing wave field with a polarization gradient a slightly more complex situation arises. We then have to include the motion of the atom along the standing wave axis. For the special case of an atom with a $F = 1 \rightarrow 1$ transition there is a dark state which is also an eigenstate of the kinetic energy [8]. This stationary dark state facilitates VSCPT cooling. For atoms with larger integer angular momenta stationary dark states are not found in the considered light field, i.e., there are no dark states which are also eigenstates of the kinetic energy. Consequently the atom cannot remain decoupled from the light field [9].

In the case of a periodically pulsed standing wave with polarization gradient the atom kinetically evolves in the time between successive pulses. The kinetic evolution can lead to a revival of the dark state [10,11], where the revival time depends on the atomic momenta along the standing wave axis. This revival of the dark state can be periodic. An atom can therefore remain in the periodically pulsed standing wave without excitation if it is in a state that evolves to a dark state each time the standing wave is switched on. These states are superpositions of states with different momenta and will be referred to as light pulse synchronously recurring dark states (LSR dark states). They exist only for discrete pulse frequencies (for $F \geq 2$) and have discrete momenta. The LSR dark states are populated by optical pumping and the atomic population accumulates in these states after a sufficiently long sequence of pulses. The cooled atomic momentum distribution then shows the momenta of LSR dark states, which results in a comblike distribution (Fig. 1).

Now consider the total Hamiltonian

$$H = P^2/(2M) + H_A + \eta(t)V ,$$

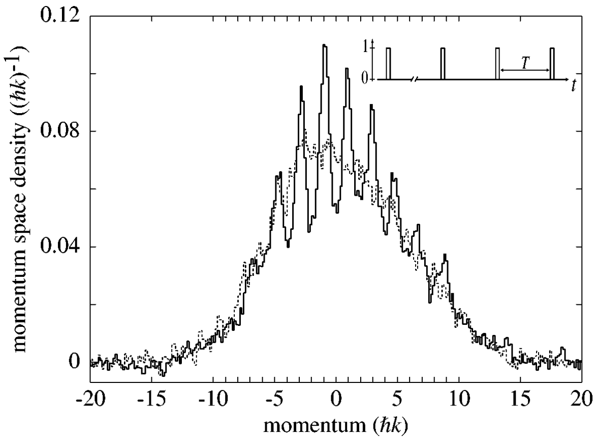

FIG. 1. Solid line: cooled momentum distribution. Dotted line: initial distribution. Inset: plot of the periodic sequence of standing wave pulses. The pulse separation for the cooled distribution is $T = 35\ \mu\text{s} = \tau_r/8$.

where P is the atomic momentum operator, M the atomic mass, and H_A the Hamiltonian of the internal atomic states. The interaction Hamiltonian of the atoms with the optical standing wave is given by V. The function $\eta(t)$ describes the time dependence of the interaction pulses and is illustrated in the inset of Fig. 1. Dark states are not coupled to any other atomic state by the interaction V, i.e., they are found by solving $V|\psi^{\text{dark}}\rangle = 0$. The dark states are populated by optical pumping [12] during each of the light pulses. The atomic evolution between the pulses is coherent and there is no dissipation. Hence the propagation is described by $T_t = \exp[-\frac{i}{\hbar}(P^2/2M + H_A)t]$. The condition $V(T_t|\psi^{\text{dark}}\rangle) = 0$ defines the recurrence of a given dark state and allows us to calculate its revival times t. The revival of the dark states is periodic.

Assume that the frequency of the standing wave is near resonant with respect to a single atomic transition. Then the interaction can be reduced to the transitions between two Zeeman manifolds. Further consider that the standing wave consists of two counterpropagating waves with circular polarizations inducing σ^+ and σ^- transitions between the Zeeman manifolds [13]. For transitions with a total angular momentum $F \geq 2$ of the ground state manifold the revival times of the dark states are discrete. The $F = 2 \rightarrow 2$ transition [14] of the ^{87}Rb D_1 line is studied in the experiment. The dark states of this system are given by

$$|\psi_p^{\text{dark}}\rangle = \sqrt{\tfrac{3}{8}}\,\left|{}^{p-2\hbar k}_{m=-2}\right\rangle + \sqrt{\tfrac{1}{4}}\,\left|{}^{p}_{m=0}\right\rangle + \sqrt{\tfrac{3}{8}}\,\left|{}^{p+2\hbar k}_{m=+2}\right\rangle,$$

where $\left|{}^{q}_{m}\right\rangle$ describes a ground state with the angular momentum $F_z = m\hbar$ and the momentum q along the standing wave axis (where $k = 2\pi/\lambda$ is the light wave vector). Each dark state is a superposition of three momentum states with different magnetic quantum numbers and has a mean momentum p. From the above condition we calculate the dark states that recur. Their mean momenta are

$$p = p_m^{(\ell)} = \frac{m}{\ell}\,2\hbar k + \hbar k\,,$$

where ℓ, m are integers. The number ℓ determines the revival time

$$t_\ell = \ell\tau_r/8\,,$$

where $\tau_r = 2\pi/\omega_r$ ($\omega_r = \hbar k^2/2M$) is the recoil time [15].

To cool the atoms the standing wave is switched on with a pulse separation of $T = n\tau_r/8$ ($n = 1, 2$). Each pulse populates the dark states by optical pumping. Dark states with one of the mean momenta $p_m^{(n)}$ remain in the periodically pulsed standing wave without further excitation. Atoms which are not in these LSR dark states couple to the standing wave and can be excited. Each spontaneous emission of a photon changes the momentum of the atom, and the atom can decay to a LSR dark state. The cooled momentum distribution shows peaks at the momenta of LSR dark states. The width of the peaks can become narrower than the single photon recoil. The velocity selectivity is due to the kinetic evolution between the pulses.

An intuitive picture describing the revival of the LSR dark states can be derived from the spatial motion of the atomic matter waves. Two plane atomic waves (with momenta p_1, p_2) can be written as a product of an envelope function and a carrier wave of average wave vector and frequency. The envelope describes the spatial pattern of varying amplitude formed by the atomic waves. It also determines the spatial variation of spin polarization. For a dark state, this spatial pattern is adapted [8,13] to the spatial polarization pattern of the light field, so that its excitation by the light field vanishes at any point in space. Now consider the motion of the atomic wave pattern. When the atomic wave pattern has moved by a multiple of the spatial period of the optical standing wave ($\lambda/2$), the excitation to the excited state vanishes again and a revival of the dark state occurs. The velocity of the atomic wave pattern is given by $v = \omega^{\text{env}}/k^{\text{env}}$, where $\omega^{\text{env}} = \frac{1}{2\hbar}(p_2^2 - p_1^2)/2M$ is the cycle frequency and $k^{\text{env}} = \frac{1}{2\hbar}(p_2 - p_1)$ the wave vector of the atomic wave pattern. For a dark state k^{env} equals the wave vector of the optical standing wave.

For the $F = 2 \rightarrow 2$ transition the dark state is a superposition of three momentum states. Therefore we have to consider two atomic wave patterns: They are formed by the two pairs of atomic waves with the magnetic quantum numbers $m = -2, m = 0$ and $m = 0, m = 2$. Each pair couples to a common excited state. A dark state is formed if both atomic wave patterns are adapted to the light field for vanishing excitation. The two patterns move at the velocities $v_\pm = \frac{p}{M} \pm \frac{\hbar k}{M}$. Solving $v_- t = n\frac{\lambda}{2}$ and $v_+ t = (n + m)\frac{\lambda}{2}$ gives the discrete revival times t and the corresponding mean momenta p of the recurring dark states as already listed above [16]. For systems with an angular momentum $F < 2$ the dark states have only two momentum components so that for any time t a series of momenta p with recurring dark states is found.

The experiment is performed with the same apparatus as described in Ref. [17]. A cloud of magneto-optically trapped ^{87}Rb atoms is accelerated downwards (Fig. 2). The cloud arrives with a speed of 3.2 m/s and a density of $n \approx 10^8$ cm^{-3} in the interaction region, which is shielded with mu-metal against magnetic fields to below 0.5 mG. There the atoms interact with a horizontally aligned $\sigma^+ - \sigma^-$ standing wave having a vertical Gaussian waist of 0.72 mm. The light field is tuned $\Delta = 2.7\Gamma = 2\pi \cdot 15$ MHz to the blue of the $F = 2 \rightarrow 2$ transition of the D_1 line, where $\Gamma^{-1} = 28$ ns is the lifetime of the excited states. Each running wave has a peak intensity of 32 mW/cm^2, which corresponds to a resonant Rabi coupling [14] of $\Omega = 2.3\Gamma$ and to an excitation rate of $\Gamma' = 0.18\Gamma = (0.16\ \mu\text{s})^{-1}$ (on the $F = 2 \rightarrow 2$ transition). An acousto-optical modulator is used to switch the standing wave on for intervals of $\tau = 3\ \mu$s alternating with dark intervals of $T = \tau_r/8 = 35\ \mu$s (corresponding to $n = 1$). During the interaction time of 0.54 ms the atoms are subjected to 14 standing wave pulses. To recycle atoms that have decayed to the $F = 1$ ground state manifold a continuous standing wave overlaps. It is tuned to the $F = 1 \rightarrow 2$ transition of the D_2 line. Its single pass Rabi coupling is $\Omega_{12} = 0.44\Gamma$, which corresponds to an excitation rate of $0.2\Gamma = (0.1\ \mu\text{s})^{-1}$. Both light fields are derived from grating stabilized laser diodes. The laser beams are spatially filtered to achieve Gaussian modes. The standing waves are formed by retroreflection off a mirror, which is 13 cm away from the interaction region. A quarter wave plate in front of the mirror is used to provide the $\sigma_+ - \sigma_-$ polarization of the standing wave. The atomic momentum distribution along the standing wave axis is measured as indicated in Fig. 2 and described in Ref. [17]. The detection is independent of the internal atomic state. The measurement is integrated over 1000 atom clouds extracted from the magneto-optical trap at a rate of 1 s^{-1}.

Figure 1 shows the momentum distribution of the cooled atoms for a pulse spacing of $T = 35\ \mu$s. The comblike structure with $2\hbar k$ spacing between the subrecoil cold peaks stems from atoms trapped in LSR dark states. The peaks occur at odd multiples of $\hbar k$, as we expect for $n = 1$ ($T = 1\tau_r/8 = 35\ \mu$s). Each LSR dark state contributes to three neighboring peaks. The width of these peaks is determined by a best Gaussian fit as $\sigma = 0.3\hbar k$, which approaches the improved resolution limit of our detection system. The dotted line in Fig. 1 represents the initial distribution (measured with both standing waves off). It has a best Gaussian width of $\sigma = 5.4\hbar k$. We observe no loss of atoms to high momenta.

To investigate the evolution of the LSR dark states we have measured a series of momentum distributions varying the time T between the pulses. Figures 3(a)–3(c) show the measurements for $T = 30$, 35, and 40 μs. A lower contrast is observed in the distributions for $T = 30$ and $T = 40\ \mu$s. LSR dark states which are completely decoupled from the standing wave do not exist for these pulse spacings. The occurring excitations make the accumulation less efficient as compared to $T = 35\ \mu\text{s} = \tau_r/8$ ($n = 1$). A further increase of the pulse spacing to $T = 60\ \mu$s completely washes out the comblike structure. For $T = 2\tau_r/8 = 70\ \mu$s [Fig. 3(d)] a momentum comb appears again with a spacing of $\hbar k$, as expected for the $n = 2$ resonance. These four measurements have been performed with slightly different parameters of the pulsed standing wave: $\Omega = 1.3\Gamma$, $\Delta = 14\Gamma$, $\Gamma' = 8 \times 10^{-3}\Gamma$, 1.37 mm waist. The atoms are subjected to 28 standing wave pulses during the interaction time. The parameters for the field of the recycling laser are $\Omega_{12} = 0.2\Gamma$,

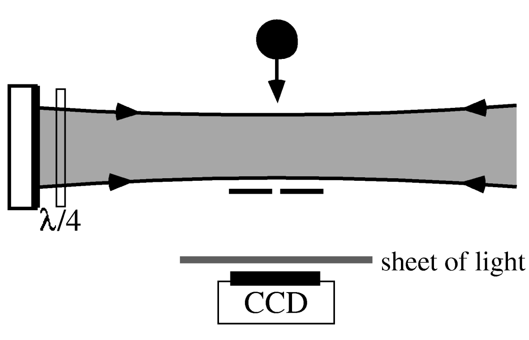

FIG. 2. Experimental setup. The atoms are cooled in a standing wave. The transverse momentum distribution is detected by spatially resolved fluorescence imaging following a free flight expansion after passing through a pinhole. See text and Ref. [17].

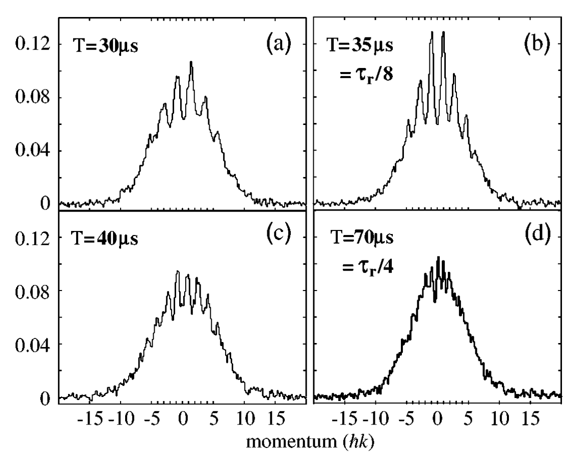

FIG. 3. Momentum distributions obtained for different separations of the standing wave pulses. See text. Vertical axis: momentum space density in units of $(\hbar k)^{-1}$.

1.6 mm waist. A three times narrower initial distribution yielded sufficient contrast after integration over 200 atom clouds.

The measurements presented here are performed in a nonclassical regime. For illustration imagine a classically localized atom, which has been optically pumped to an internal dark state. If it is at rest, no further excitation occurs—independent of the standing wave being permanently on or pulsed. Hence one would expect to find atoms especially at zero momentum. In contrast we observe a minimum in the atomic momentum distribution at $p = 0$ (for $n = 1$) due to the delocalization of the atoms.

Our scheme can be extended to two and three dimensions and to transition schemes of the type $F \rightarrow F$ and $F \rightarrow F - 1$ [18]. It might find particular interest as a fast cooling technique for atoms which have transition frequencies that can only be excited using pulsed laser sources, as, e.g., the Lyman-α transition of hydrogen. Writing extremely narrow and closely spaced nanostructures on a substrate is another tempting application for our cooling scheme. Each momentum component of a transversely cooled atomic beam could be focused on a narrow line in the focal plane of a cylindrical lens. Adequate lenses can be realized by the optical potential that an atom experiences in a far off-resonant standing wave [19]. The spacing between the lines would be determined by the focal length of the lens and by the angle enclosed by the momentum components. Momentum combs with even closer spacings than presented here can be achieved if longer pulse separations ($n > 2$) are applied. Then the LSR dark states can have momenta which are integer fractions of the recoil momentum $\hbar k$.

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