Momentum Transfer in Laser-Cooled Cesium by Adiabatic Passage in a Light Field

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We have observed transfer of momentum and ground state population in laser-cooled cesium by adiabatic following of a slowly evolving light field. In this new technique for mechanical manipulation of atoms, spontaneous emission is suppressed since the atoms evolve in a "dark" state that follows the light field. This means that the phase coherence of the atom is preserved so that this technique is useful in the realization of coherent atomic beam splitters and mirrors. Our experimental results are in good agreement with optical Bloch equation calculations.

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Atom optics [1], the manipulation of atoms in analogy to manipulation of light, requires atomic analogs to optical elements. For example, atom interferometers require beam splitters and mirrors that preserve atomic coherence. Recently, momentum transfer by adiabatic passage was proposed [2] as a fundamentally new and promising technique for the coherent manipulation of atoms with light. This paper (and Ref. [3]) reports the first experimental demonstration of mechanical action on atoms by this technique. We demonstrate a momentum transfer of eight photon momenta, as well as the accompanying population transfer, in a nine-level system and make a quantitative comparison with a realistic model that, for the first time, includes off-resonant interactions as well as the adiabatic interaction.

Beam splitters and mirrors are coherent if they can be used to split and recombine an atomic beam so as to produce interference. Spontaneous emission relaxes the coherence and is avoided by keeping the atom in a coherent superposition of ground states, determined by the polarization of the applied light that is nonabsorbing [4]. An atom in such a dark state (which here is also a superposition of momentum states) can adiabatically follow a changing light field, transferring population and momentum coherently. As with similar techniques used to adiabatically transfer atomic [5] and molecular [6] populations, there are no stringent requirements on field power or interaction time, but only the usual requirement that the interaction proceed slowly enough to be adiabatic [7]. The process is therefore not sensitive to small changes in the field power or interaction time, as it is in some other techniques (see below). Besides being adiabatic, the transfer must also occur quickly with respect to relaxation times. With a dark state, the relaxation time is not the excited state lifetime (Γ^{-1}), and pulses need not be shorter than that lifetime.

As a technique for coherently imparting momentum to atoms (the action of mirrors and beam splitters), this method has advantages over existing techniques. Diffraction from material structures [8–10] and optical standing waves [11] results in many momentum states (diffraction orders) with only a small momentum difference between them. Here it is possible to produce just one (mirror) or two (beam splitter) final states with a large momentum difference. Evanescent wave mirrors [12] cause large phase shifts in the atomic wave function due to the ac Stark shift in the off-resonant field. The stability of these shifts can be problematic in interferometry. Raman π and $\pi/2$ pulses, used as mirrors and splitters [13], also have such shifts, and in addition are quite sensitive to the pulse power and interaction time. Adiabatic passage, performed on resonance with the atom in a dark (or nearly dark) state, avoids phase shifts in atoms without hyperfine structure. The magneto-optic beam splitter recently demonstrated [14] does have large momentum transfer but does not result in a single final state and requires a magnetic field which can cause difficulties in some applications. The technique we demonstrate here results in $8\hbar k$ momentum transfer in a single pass with $\approx$50% efficiency using the D_2 transition in Cs. The use of a more advantageous atom or transition would lead to efficiencies near unity for even larger momentum transfer.

The relevant states for adiabatic transfer are shown in Fig. 1(a). Atoms are initially optically pumped into the $F = 4, m_F = -4$ state by a pulse of σ^- light [Fig. 1(b)] resonant on $F = 4 \rightarrow F' = 4$. Approximately half of the atoms are lost into the $F = 3$ ground state (dependent on the initial m_F-level distribution). After optical pumping, a second σ^- pulse is applied, followed by a temporally overlapping, counterpropagating σ^+ pulse [Fig. 1(b)]. For $\sigma^\pm$ light, $m_F = \pm 4$ is dark, and for any superposition of σ^+ and σ^-, there is a superposition of the even ground state m levels which is dark [2]. As the light field varies from σ^- to σ^+, the atoms remain dark, starting from $m_F = -4$ and ending in $m_F = 4$. In the absence of spontaneous emission, and for counterpropagating laser fields, the levels connected by the atom-laser Hamiltonian are members of a closed momentum family, each

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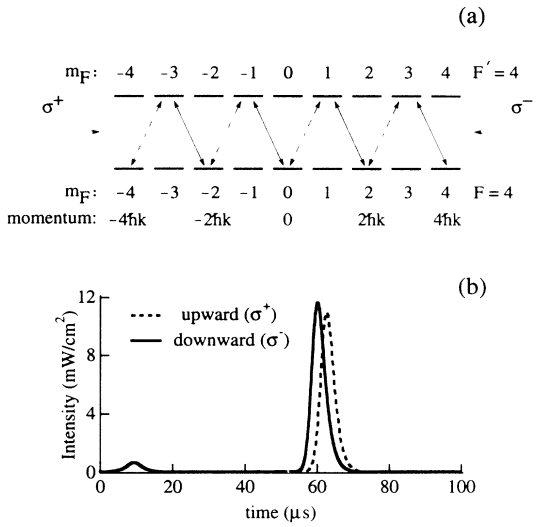

FIG. 1. (a) Momentum and population transfer for $F = 4 \rightarrow F' = 4$. The $p = 0$ momentum family is shown. (b) Typical optical pumping and adiabatic transfer pulse sequence. Peak intensity corresponds to a Rabi frequency of 11 MHz on a transition with a Clebsch-Gordan coefficient of 1.

m_F having associated with it a distinct momentum. The momentum family containing $p = 0, m_F = 0$ (the "$p = 0$" family) is shown in Fig. 1(a). The $m_F = +4$ final state has an associated momentum of $4\hbar k$, an increase of $8\hbar k$ over the $m_F = -4$ initial state.

In our experiment, a cesium atomic beam is chirp cooled and loaded into a magneto-optic trap (MOT) [15]. The MOT magnetic field is turned off and atoms are cooled in optical molasses [three-dimensional (3D) followed by 1D cooling] to 3–6 μK. A small magnetic field (typically $B_0 \approx 4$ μT) along the vertical axis is always present to preserve the orientation of the atoms. Finally, the molasses light is turned off and the atoms fall through a probe laser located 57.5±1.0 mm below the MOT. The probe laser is tuned to $F = 4 \rightarrow F' = 5$, so that only atoms in the $F = 4$ ground state are detected. This time-of-flight (TOF) method allows measurement of both the initial velocity and the velocity spread (temperature) of the atoms. The laser pulses [Fig. 1(b)], generated by acousto-optic modulators, are applied within 300 μs of the time the molasses is turned off, before the atoms accelerate significantly. The pulses travel along the vertical axis so momentum transfer appears as a change in the TOF to the probe. We demonstrate momentum transfer by comparing the TOF for atoms subjected only to optical pumping with the TOF for atoms subjected to the full pulse sequence of Fig. 1(b). Typical TOF signals are shown in Fig. 2. In this example, the later arrival (3.12 ms) of the atoms subjected to the transfer pulse sequence corresponds to a momentum transfer of $8.5 \pm 0.5\hbar k$. The random uncertainties, due to the precision with which the TOF can be determined, are $\pm 0.1\hbar k$, but there are systematic uncertainties, here and in Fig. 4, of $\pm 0.5\hbar k$

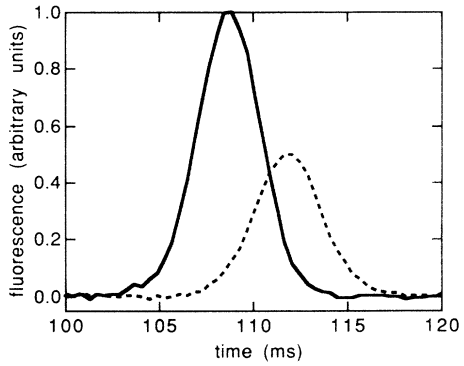

FIG. 2. TOF signals for atoms subjected only to the optical pumping pulse (solid line) and to the entire transfer sequence (dashed line). The delay between the pulses was 2.23 μs. The maximum intensity was about 10 mW/cm^2.

due to a small (≈ 3 μT/cm) background gradient in the magnetic field.

We probe the populations of the magnetic sublevels by applying a vertical magnetic field gradient of about 2 mT/cm for the first 25 ms after the atoms are released. Atoms in different m_F sublevels receive different impulses from the gradient, and the TOF for atoms dropped directly from molasses separates into nine peaks. The small field B_0 preserves the orientation of the atoms as the gradient field is turned on. An example of population transfer is shown in Fig. 3. The early arrival of the atoms that are only optically pumped (solid line) corresponds to the arrival time of $m_F = -4$, and the late arrival of the transferred atoms (dashed line) corresponds to that of $m_F = 4$. The small peaks at arrival times corresponding to $m_F = 3$ and $m_F = 2$ result primarily from a misalignment between the optical and magnetic axes. A larger B_0 results in better atomic orientation (a single peak at $m_F = \pm 4$) but presents other problems, discussed below.

The fraction of atoms remaining in the $F = 4$ ground state after a transfer is determined from the ratio of the

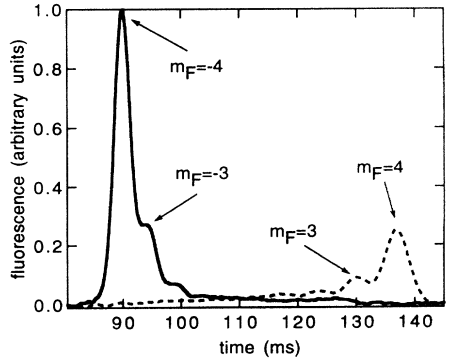

FIG. 3. Here a magnetic field gradient has been applied as the atoms fall so that the m_F-level populations can be resolved. The solid line is the TOF signal after optical pumping and the dashed line is the TOF signal after a transfer.

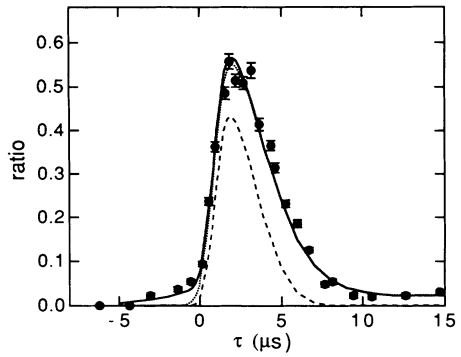

FIG. 4. Efficiency of transfer vs pulse separation τ. Solid circles are the fraction of atoms remaining in $F = 4$; the solid line is the corresponding calculation. The dotted line is the fraction calculated to end up in $m_F = 4$; the dashed line is the fraction calculated to be coherently transferred.

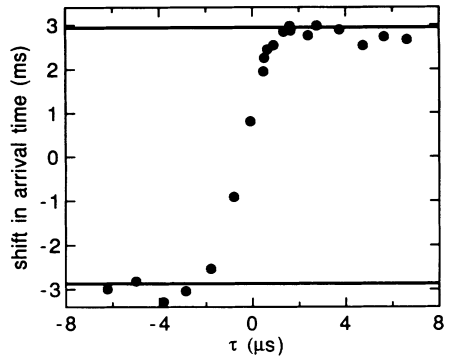

FIG. 5. If the optical pumping pulse is omitted, transfer in either direction is possible. The shift in the TOF vs τ is shown. The solid lines are $\pm 8\hbar k$ transfer.

integrals of TOF signals such as those shown in Fig. 2. In Fig. 4 we plot this fraction vs pulse separation τ. Solid circles are data and the solid line is a solution of the optical Bloch equations. A single parameter that accounts for a small drift velocity and magnetic field (which couple the atom out of the dark state; see below) has been adjusted to fit the data. If τ is too large, the process is not adiabatic; the atoms do not remain dark and are optically pumped into $F = 3$, giving no signal. For $\tau < 0$, the initial state is not dark, and again atoms are lost to $F = 3$. Near the peak efficiency, the theory predicts that 57% of the atoms are transferred into $m_F = 4$ (dotted line), with only 2% in $m_F = 2$, and the remainder pumped into $F = 3$. Of those arriving in $m_F = 4$, some have undergone a spontaneous emission into $F = 4$. The fraction predicted to have been coherently transferred (no spontaneous emission) is shown as a dashed line. At the peak, 42% of the atoms have undergone only coherent interactions. We see no heating in the transfer, consistent with a mainly coherent process. The population transfer cannot be explained by optical pumping on the $F = 4$ to $F' = 4$ transition (σ^+ pumping from $m_F = -4$ to $m_F = +4$ has an efficiency of only 1%).

If the optical pumping pulse is omitted, the first transfer pulse pumps the atoms into the dark state, and transfer in either direction can be achieved depending on which pulse occurs first. (Normally we have used a separate optical pumping pulse to better define the initial conditions.) In Fig. 5, we plot the change in the TOF of the atoms vs τ. For positive (negative) τ, the downward σ^- (upward σ^+) pulse occurs first and the atoms remaining in $F = 4$ are kicked upward (downward), and are expected to arrive 2.94 (2.86)± 0.20 ms later (earlier) at the probe.

For Gaussian pulses with full width at half maximum (FWHM) equal to T and separation $\tau = T$, the adiabaticity requirement [7] for $\Omega \gg \Gamma$ is $\Omega T \gg 1$ where Ω is the peak amplitude of the smallest Rabi frequency involved in Fig. 1(a). It can be shown [16] that if $\Omega \ll \Gamma$, an adiabatic interaction is still possible, and requires $\Omega^2 T/\Gamma \gg 1$. For $\Omega = \Gamma/2$, the requirement is $2\Omega T \gg 1$. In this experiment, $\Omega \approx 25 \times 10^6$ rad/s, and $\Gamma = 33 \times 10^6$ rad/s, so that $\Omega \approx \Gamma/2$. Our pulses, with $T = 4.2$ μs (FWHM), are sharper than a Gaussian, so the adiabatic condition is somewhat more stringent, but a detailed calculation shows that we satisfy it.

Various loss mechanisms in the real system put limits on both T and Ω. Off-resonant transitions to other excited states in the $P_{3/2}$ manifold are the major reason coherent transfer is only 42%. The resulting spontaneous emission either transfers the atoms to $F = 3$ or destroys the coherence of the transfer. These problems could be avoided by using, e.g., the $F' = 4$ state in the $P_{1/2}$ manifold. The splitting between the excited hyperfine levels for this D_1 transition is large enough that >90% of the atoms could be coherently transferred.

The remaining limitations are due to coupling of the dark state to other states. For an $F > 1$ system, the ground state magnetic sublevels comprising the dark state have different kinetic energies due to their different momenta, even for the $p = 0$ family. Thus the "dark" state is not perfectly dark, has an admixture of excited state, and can decay. In our case, a small initial velocity v_0 and the orientation field B_0 contribute Doppler and Zeeman shifts to the splitting of the ground state and aggravate this problem. For example, for the data shown in Fig. 2, the TOF of the optically pumped atoms was 108.74±0.01 ms (statistical uncertainty), corresponding to a (upward) $v_0 = +0.4 \pm 1.0$ cm/s (uncertainty in distance to the probe). Since neither v_0 nor B_0 is well known, the splitting of the ground state sublevels was varied in the calculations of Fig. 4. In this fashion we determined that the total splitting between adjacent sublevels was 30 kHz. This gives, e.g., $v_0 = +1.3$ cm/s and $B_0 = 4.3$ μT, assuming v_0 to be due to the effect of B_0 on atoms in the 1D σ^+-σ^- optical molasses that precedes the transfer [17]. (This also requires a probe distance of 56.5 mm to be consistent with the TOF.) With these pa-

rameters, the width of the "dark" state is calculated to be always less than 50 kHz. If we start in the $p = 0$ family [$v_0 = -4\hbar k/m$ or -1.41 cm/s for $m_F = -4$; see Fig. 1(a)], the coherent transfer efficiency should increase from 42% to 49%. While these calculations account for v_0, they do not account for velocity spread, so 49% may be a slight overestimate.

The coherence of the momentum transfer has yet to be directly demonstrated by interference. This could be done in our experimental setup using the $F = 4 \rightarrow F' = 3$ transition of the Cs D_2 line, for which there are two dark states (e.g., $F = 4, m_F = 3$ and 4 for σ^+ illumination). We can form a coherent superposition of these dark states, transfer both of them simultaneously, reverse the transfer, and observe the final state. The relative phase of the two dark states will evolve differently since they experience different light shifts from off-resonant transitions during the transfer. The composition of the final state will have an oscillatory dependence on the differential phase shift, directly demonstrating coherence. The initial superposition can be created by optically pumping the atoms into the $F = 4, m_F = 4$ state along a quantization axis rotated from the one used in the transfer.

The adaptation of this technique to a beam splitter has been discussed elsewhere [2,3]. Here, we have demonstrated an atom "deflector" that could be used as a mirror. In atoms without hyperfine structure (e.g., metastable noble gases) the efficiency is not limited by off-resonant transitions, and may be nearly 100% with sufficient laser intensity. This allows many repeated transfers [3], resulting in a very large momentum change, and avoids phase shifts due to off-resonant transitions.

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