Efficiencies of adiabatic transfer in a multistate system

R. M. Godun, C. L. Webb, M. K. Oberthaler, G. S. Summy, and K. Burnett
Clarendon Laboratory, Department of Physics, University of Oxford, Oxford OX1 3PU, United Kingdom
(Received 23 October 1998)

We present a theoretical and experimental study of the efficiency of adiabatic transfer between the Zeeman substates of the cesium ground level, using the $D1$ $F=4\rightarrow 4'$ transition. In order to understand the application of the adiabatic condition to such multistate systems, we examine the separation of their energy eigenstates as a function of the number of participating states. We present a systematic investigation of the physical factors affecting the efficiency of transfer in a multistate system and we see that velocity selection plays an important role in these calculations. We use the theory to compare the suitability of adiabatic transfer with $F=1\rightarrow 1'$ and $F=4\rightarrow 4'$ transitions for atom optics. [S1050-2947(99)06505-1]

PACS number(s): 42.50.Vk, 03.75.Dg

I. INTRODUCTION

Momentum transfer during adiabatic passage has been the subject of a number of experimental and theoretical investigations [1–4]. Discussions of the efficiency (the ratio of population in the final and initial states), however, have generally been confined to λ systems where atoms are transferred between two Zeeman ground states with coupling via a third, excited state [5]. This paper presents theoretical models and experimental results for adiabatic transfer efficiency in a multistate system, the cesium ground level $F=4$. A system with a higher number of states is attractive for atom interferometry because the momentum transfer in a single pulse can be made much greater than in a system with a lower number of states. This in turn can lead to larger spatial separations between the interferometer arms for a multistate system. The disadvantage of multistate systems, however, is that the transfer efficiency can be lower for a given laser field intensity. Just how much lower this may be is, of course, a crucial issue.

The atom interferometer we have reported previously [6] uses adiabatic transfer to separate spatially two wave packets. The atomic source is laser cooled cesium and the transfer is performed on the ground level $6^2S_{1/2}F=4$ with light resonant on the $D1$ transition $6^2S_{1/2}F=4\rightarrow 6^2P_{1/2}F'=4$, see Fig. 1. We have used a model of this system and produced numerical predictions for various experimental arrangements in order to examine the theoretical limits to the efficiency we could achieve.

Spontaneous emission during the transfer process produces dephasing and must be reduced to a minimum. Population in an atom's excited levels throughout the transfer process must therefore be avoided, even though the atom may be illuminated with on-resonant light. This is achieved using transfer via a ''dark state,'' a state which is unable to undergo transitions to the excited level.

In the next section we describe the formation of a dark state. We then go on to describe our theoretical model of the transfer process and give a systematic investigation of the factors affecting transfer efficiency. We show that a major factor is the number of states involved in the transfer. This result, which may at first be surprising, is important when choosing which atomic transition to use, or maybe even which atom to use. We will also look at the kinetic energy the atom picks up in each Zeeman ground state and show that this leads to velocity selectivity which has a large effect when considering the overall efficiency from an ensemble of atoms with a velocity distribution. The effect of off-resonant levels on the transfer efficiency is also discussed. Finally we use the model with all these components to compare the efficiency of two systems with different numbers of states for use in atom interferometry.

We hope that this discussion will be helpful to other readers wishing to gain an understanding of adiabatic transfer efficiency in their own system. By applying our method with data specific to their system, an understanding of the relative importance of different effects can be gained, as well as a prediction for the expected efficiency. This is vital for the planning of any experiment in which adiabatic transfer might be used.

II. ADIABATIC TRANSFER

Consider, as in the case of our experiment, atoms irradiated with light resonant on the $D1$ $F=4\rightarrow 4'$ transition as

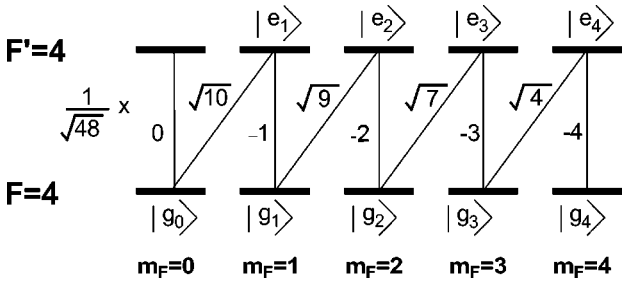

FIG. 1. Relevant m_F states in the $D1$ transition between $6^2S_{1/2}F=4$ and $6^2P_{1/2}F'=4$. The transition amplitudes are also marked.

indicated in Fig. 1. If atoms are prepared initially in the $m_F=0$ state and are exposed to π light, there will be no excitation. If the intensity of π light is slowly decreased, while the intensity of an orthogonal beam of σ^+ light is increased, the eigenstate which is dark will slowly evolve into a superposition of different m_F states. The atoms will remain in this slowly changing dark state if adiabaticity as discussed in Sec. III is maintained. As the incident light changes from π to σ^+, the atoms are transferred from $m_F=0$ to $m_F=+4$, which is a dark state for σ^+ light. This transfer occurs without ever populating the excited level. The atoms exchange eight photons with the optical field during the transfer and will thus pick up a net momentum from the photons. A consequence of this process is that the constituent m_F states possess different kinetic energies. This will prevent strict darkness being achieved, but does not prohibit adiabatic transfer; it lowers the efficiency.

FIG. 2. Eigenenergies for all the eigenstates in each $F\rightarrow F$ transition from $1\rightarrow 1'$ to $4\rightarrow 4'$. The energies are as a function of progress through the transfer and have assumed equal couplings between all the levels. The calculation was performed with the Rabi frequency set equal to twice the spontaneous decay rate from the upper level. The atomic recoils have also been included.

III. ADIABATIC CONDITION

The main loss from adiabatic transfer is excitation into other, nondark states; thus to optimize the efficiency one has to satisfy an adiabatic condition. Messiah [7] states that a change is adiabatic if the rate of change of any eigenvector $|i\rangle$ is much less than the Bohr frequency for the transition from $|i\rangle$ to its nearest coupled neighbor.

This condition can be understood intuitively in terms of the uncertainty principle. The longer the time of the transfer, the smaller the uncertainty in energy and so the lower the probability of atoms making a transition from the zero energy of the dark state to another eigenstate. Thus longer transfer times produce less loss to the other states and hence higher efficiencies. Higher powers similarly lead to greater efficiencies because the increased coupling of the atom to the light field leads to larger energy gaps between the eigenstates, lowering the probability of a transition out of the dark state.

For a λ system, the condition reduces to that of [5]

$$\omega_{ij}T\gg 1, \tag{1}$$

where T is the total transfer time and ω_{ij} is the frequency difference between the eigenstate $|i\rangle$ and its nearest coupled neighbor $|j\rangle$. For the λ system, $\omega_{ij}\sim\Omega$, the Rabi frequency of the interaction transition. Equation (1) also demonstrates that the transfer can be made more efficient by increasing either the power or transfer time. To apply this equation to the $F=4\rightarrow 4'$ system used in our interferometer, however, ω_{ij} needs to be known. One might naively think that ω_{ij} would not depend on the number of states involved, but this is not so: ω_{ij} is much smaller in a multistate system. To demonstrate this, we have calculated the eigenstates for systems with varying numbers of states. Their eigenvalues are plotted in Fig. 2 as a function of progress through the transfer. In this calculation, we assumed for simplicity that all the transitions have equal couplings with the light field and included the effects of atomic recoil. The recoil effects are not seen on the scale of Fig. 2. We see that the eigenvalues of the $4\rightarrow 4'$ system are more closely spaced than those of a system with less states and ω_{ij} is correspondingly lower in systems with a higher number of states. We should therefore expect transfer efficiencies for a given field strength to be lower in multistate systems. This is a very important point. One might at first think that efficiency results for an $F=1\rightarrow 1'$ system, which are easier to calculate, may be applied directly to multistate systems. This is not the case and care must be taken when estimating the potential efficiency for a higher-state system. A full theoretical model of the process is needed to predict quantitatively the efficiencies attainable on the $F=4\rightarrow F'=4$ transition of the $D1$ line in cesium and this is what we turn to next.

IV. THEORETICAL MODEL

The model took account of as many of the experimental parameters as possible. The Schrödinger equation was solved for a nine state model system: the five ground state magnetic sublevels $m_F=0\rightarrow m_F=4$ and four excited state magnetic sublevels $m_{F'}=1\rightarrow m_{F'}=4$. Atoms were always prepared in the ground $m_F=0$ state, so that with only π and σ^+ light there was no need to include the excited state $m_{F'}=0$. The negative m_F states could also be neglected because there was no possibility of them coupling to the light fields.

The evolution of the system is governed by the Schrödinger equation

$$i\hbar\frac{d|\Psi\rangle}{dt}=H|\Psi\rangle \tag{2}$$

where, in the dressed state picture the Hamiltonian is

$$H=\begin{pmatrix}
E_{g_0} & \sqrt{10}q\hbar\Omega_\sigma & & & & & & & & \\
\sqrt{10}q\hbar\Omega_\sigma & E_{e_1} & -q\hbar\Omega_\pi & & & & & & & \\
 & -q\hbar\Omega_\pi & E_{g_1} & \sqrt{9}q\hbar\Omega_\sigma & & & & & & \\
 & & \sqrt{9}q\hbar\Omega_\sigma & E_{e_2} & -2q\hbar\Omega_\pi & & & & & \\
 & & & -2q\hbar\Omega_\pi & E_{g_2} & \sqrt{7}q\hbar\Omega_\sigma & & & & \\
 & & & & \sqrt{7}q\hbar\Omega_\sigma & E_{e_3} & -3q\hbar\Omega_\pi & & & \\
 & & & & & -3q\hbar\Omega_\pi & E_{g_3} & 2q\hbar\Omega_\sigma & & \\
 & & & & & & 2q\hbar\Omega_\sigma & E_{e_4} & -4q\hbar\Omega_\pi & \\
 & & & & & & & -4q\hbar\Omega_\pi & E_{g_4} &
\end{pmatrix},$$

with $q=1/(2\sqrt{48})$, due to the branching ratio of the cesium $D1$ $4\rightarrow 4'$ transition.

The diagonal elements of the Hamiltonian matrix represent the energies of each of the states pictured in Fig. 1. These energies are not degenerate, even in the dressed state basis, because they include the kinetic energy differences arising from each sublevel having a different external momentum as a result of photon exchange with the light field. The off-diagonal elements represent the couplings between different states due to the light field. They are simply the Rabi frequencies of the interaction which have been expressed as the Rabi frequency of the atom's stretched state transition multiplied by the relevant Clebsch-Gordan coefficient.

Experimentally the light field was initially composed of π light alone whose intensity was decreased as the σ^+ component was increased. The precise form of our experiment led to Rabi frequencies with a time dependence

$$\Omega_\pi \sim \cos\left(\frac{\pi}{2}\frac{t}{T}\right),$$
$$\Omega_\sigma \sim \sin\left(\frac{\pi}{2}\frac{t}{T}\right), \tag{3}$$

where T is the total pulse time and t is the time through the pulse.

Other pulse shapes could have been created with different experimental setups but theoretical calculations [8,9] have shown that the efficiency of transfer is almost independent of pulse shape as long as the transfer process remains adiabatic.

The energies of the five ground state sublevels are not degenerate because of kinetic energy and a phase shift will develop between these states which tends to destroy the dark state [10]. An imperfect dark state will have some coupling to the excited level leading to a small population in the excited level; it is therefore important to include the effects of spontaneous decay from the upper states as these may reduce the efficiency of the transfer.

The spontaneous decay is included by the addition of $-i\hbar\Gamma/2$ to the energies of the excited states where Γ is the spontaneous decay rate out of the excited level. This is a reasonable description as long as we can assume that once an atom decays, it leaves the $F=4\rightarrow 4'$ system completely. It is however possible for an atom to decay incoherently into $F=4$. The probability that such a decay would result in a dark state component is negligible and the atom would continue to be reexcited until finally leaving the system. Whether the atoms return to $F=4$ incoherently or leave the system entirely is irrelevant to the coherent transfer efficiency which depends only on the number of *dark state* atoms left in $F=4$. For simplicity of the model, it is therefore assumed that atoms leave the system entirely once they decay out of the excited level.

In our interferometer, a double AT pulse was produced by applying the light fields described above in Eq. (3) and then reversing the amplitude function of the light fields in time. A double pulse thus returns the atoms to the initial $m_F=0$ state and avoids keeping them in the magnetically sensitive $m_F=4$ state. Figure 3 shows a plot of the evolution of the dark state during a double pulse. Note how the total probability of being in the system falls, due to spontaneous decay out of the system.

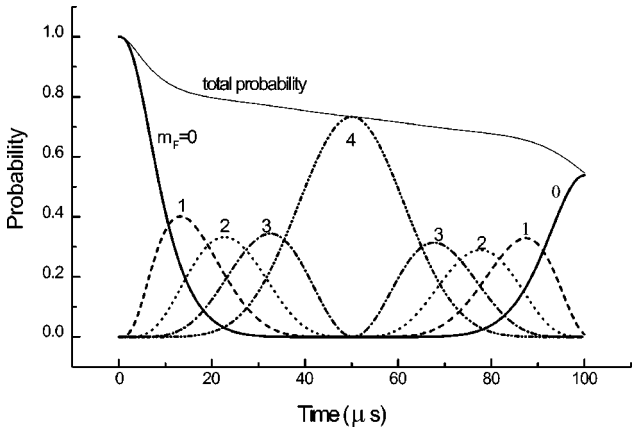

FIG. 3. Composition of the dark state throughout a double adiabatic transfer. It can be seen that the state changes from being purely $m_F=0$ to being a superposition of all m_F states to purely $m_F=4$, and back again. The total probability is also plotted so decay out of the dark state can be seen. This calculation was for a 100 μs double pulse in cesium with incident light at an intensity of 5 mW/cm^2 which is $2.5I_{\text{saturation}}$.

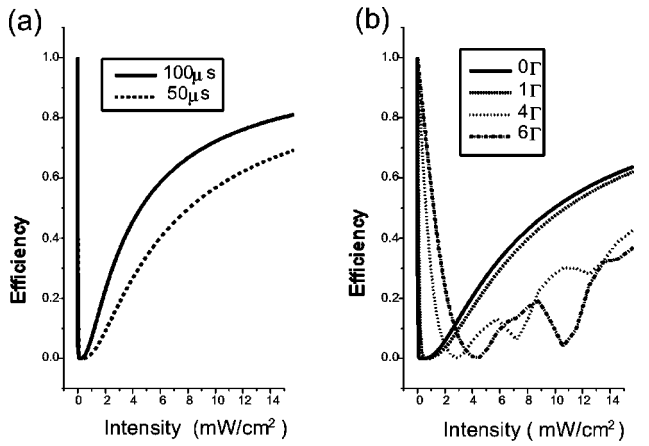

FIG. 4. Theoretical efficiencies as a function of intensity for (a) different pulse lengths at zero detuning and (b) different detunings (in units of the spontaneous decay frequency) for a 40 μs double pulse. In each case, the atoms are all assumed to have the same initial momentum—the ''optimum momentum,'' as described below.

V. THEORETICAL EFFICIENCIES

The model was used to calculate the fraction of coherent atoms in the $m_F=0$ state at the end of the transfer. This gives directly the efficiency of the process since only those atoms which have remained in the dark state will be transferred back into the initial state. Figure 4 shows plots of the efficiencies for different pulse lengths and detunings of the $F=4\rightarrow F'=4$ transfer light. All the plots show unit efficiency at zero intensity. This is expected; the atoms do not receive any light and therefore do not undergo a transfer at all. For small intensities, the efficiency falls sharply as the atoms do not receive sufficient coupling to be kept strongly in the dark state and they are very easily lost from it. As the intensity increases, the efficiency slowly rises to an asymptotic value as the coupling keeps the atoms more strongly in the dark state.

Figure 4(a) shows that for longer pulses, the efficiency is higher for a given intensity, as predicted by the adiabatic condition. Both curves tend to the same asymptotic value, so for large enough intensities ($\geqslant$200 mW/cm^2), both pulse lengths will yield an efficiency of about 98%. This was determined by extending the calculation to higher intensities. Another way to change the adiabatic condition is by changing the detuning of the light field. Detuning causes the nondark eigenenergies as shown in Fig. 2 to shift with respect to the zero energy of the dark state. Since some of the eigenstates shift closer to the dark state, a higher intensity is needed to push these levels away again and thus regain adiabaticity. This behavior is seen in Fig. 4(b) where curves representing increased detuning are shifted to higher intensity. The oscillations appearing in the efficiencies at higher detunings arise from interference between the dark state and the eigenstates which have been shifted closer by the detuning. These oscillations are not seen on resonance because they are damped out faster due to the shorter lifetime of the nondark states.

The results in Fig. 4 show the general trends of adiabatic transfer efficiency with differing pulse lengths and detunings. For a more complete model, we must include the effects of off-resonant levels and the initial velocity distribution. These will now be considered and we shall see that velocity selection plays an important role.

A. Off-resonant levels

In a real atom, there will also be many other levels, to which the transfer light can off-resonantly couple. This will produce a complex energy shift of the ground state

$$\Delta E_g=\frac{\hbar\Omega^2}{4}\left(\frac{1}{\delta}-\frac{i\Gamma}{2\delta^2}\right),$$

where Γ is the spontaneous decay rate of the upper level, δ, assumed to be much greater than Γ, is the off-resonant detuning and Ω is the Rabi frequency of the coupling. Including this energy shift in the model made a negligible difference at low intensities but at high intensities (about 10 times greater than those shown in the plots) it caused the efficiency to decay slowly down from its asymptotic value in the absence of the other levels. In our system, the effect of the off-resonant levels is small because they are so far detuned for $D1$ light.

B. Velocity selection

The kinetic energies of the states scale with the square of the momenta, thus

$$E_{m_F}=\frac{[p+(1/\sqrt{2})n_{m_F}\hbar k]^2}{2M}. \tag{4}$$

Here p is the initial momentum, n_{m_F} is the number of photons that atoms in the m_F state have received, and M is the mass of the cesium atom. The transfer process will be most efficient when the energy spacings between the m_F states within the dark state are minimized. This is because the larger the kinetic energy differences, the greater the phase differences that evolve between them and thus the lower the probability of the atoms staying in the dark state. There is an optimal initial momentum for minimizing the energy spacings and hence optimizing the efficiency.

The results for efficiency in Fig. 4 were obtained for this optimum momentum and so are the highest possible. Atoms with different momenta will undergo adiabatic passage with smaller efficiencies and adiabatic transfer is therefore velocity selective (see, for example, Ref. [11]).

This velocity selection was investigated theoretically by giving a uniform momentum distribution to the atoms before the transfer pulse and observing the width of the momentum distribution afterwards. The inset in Fig. 5 shows which velocity classes were able to pass through the transfer process.[1] Therefore if an atomic wave packet has a momentum distribution with a width greater than the range of velocity classes that can be selected, the wave packet will be narrower in momentum space after the AT pulse.

[1]The ''optimum momentum'' mentioned above was taken to be where the efficiency was a maximum in these calculations.

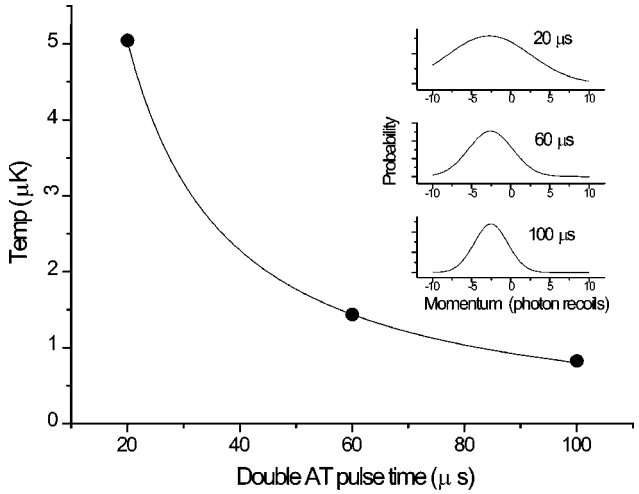

FIG. 5. The inset is a set of plots showing the momentum distribution of atomic wave packets after three different length adiabatic transfer pulses at the saturation intensity. The initial distribution in each case was unit probability for all momenta between -10 and $+10\ \hbar$k. It can be clearly seen that longer pulses lead to narrower distributions. The main curve shows the theoretical temperatures calculated from these momentum curves assuming a Maxwell-Boltzmann distribution and the three points plotted on the curve are the temperatures corresponding to the widths of the distributions in the inset.

The widths of the calculated momentum distributions were then converted to effective temperatures through the Maxwell-Boltzmann distribution and are shown as a function of pulse length in the main curve in Fig. 5. The three marked points along the curve are the temperatures corresponding to the momentum distributions in the inset. For longer AT pulses the momentum distributions were narrowed further and so the effective temperatures were reduced. Using a time of flight technique, the temperature of our atomic source was estimated to be approximately 3 μK and thus adiabatic transfer can be seen to be reducing the effective temperature of the atoms for pulses longer than about 30 μs.

In our experiments, where pulse lengths were typically greater than 40 μs, it was important to consider the effects of velocity selection on the efficiency. If, due to velocity selection, only a fraction of the atoms are able to undergo adiabatic passage across the m_F states and back, then the efficiency will only be a fraction of that calculated without the effect of velocity selectivity. The effect of velocity selection was incorporated into our predictions for overall efficiency by averaging the efficiency over a Gaussian distribution in momenta corresponding to an initial source temperature of 5 μK. The effect of velocity selection on the efficiency is obviously more marked for longer pulses as seen in Fig. 6.

VI. COMPARISON OF THEORETICAL AND EXPERIMENTAL EFFICIENCIES

We performed experiments to measure the efficiency of the adiabatic transfer in the interferometer. The cesium atoms, prepared in the ground state $|F=4, m_F=0\rangle$, underwent a double AT and the number left in the ground level $F=4$ was measured. We repeated the measurements at increasing intensities for different pulse lengths and also for different

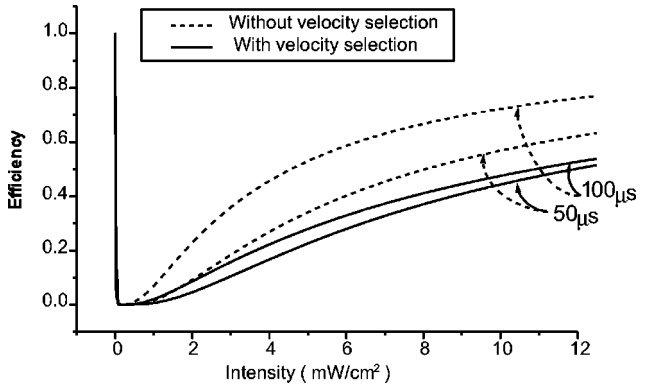

FIG. 6. The two upper curves represent the theoretical efficiencies for two different pulse lengths without the inclusion of velocity selection, just as in Fig. 4(a) and the two lower curves represent the corresponding efficiencies *with* velocity selection where the atomic source was taken to be at 5 μK.

detunings of the $F=4\rightarrow F'=4$ transfer light. Note that experimentally atoms in all m_F states of the ground level were detected, not just the dark state ones in $m_F=0$. This means that our experimental measurements do not give directly the efficiency. To be able to compare the theoretical efficiency results with experimental results we must make theoretical plots which sum over the populations in all the m_F ground states.

Figure 7 shows that there is good agreement between experiment and theory with one fitting parameter, the experimental intensity. This latter quantity cannot be accurately determined since it was not possible to measure the light intensity inside the vacuum where the atoms were located. The fact that there is such good agreement between theory and experiment shows the validity of the theoretical model and the importance of the inclusion of velocity selection. Theoretical results for other pulse lengths also showed good agreement with experimental results.

The experimental and theoretical curves for different detunings shown in Fig. 8 are not in such good agreement as those for different pulse lengths. For large detunings, the experiment yields higher populations than predicted by the

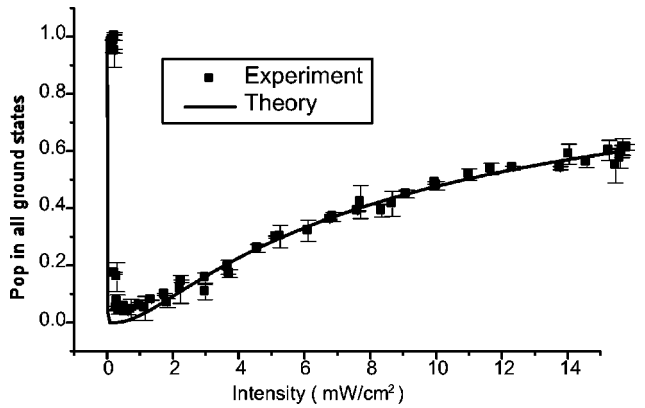

FIG. 7. The curve shows the theoretical result of population in the ground level after a 100 μs double transfer pulse, with the inclusion of velocity selection based on a 5 μK source. The points are the experimental results and the fitting parameter was the experimental intensity.

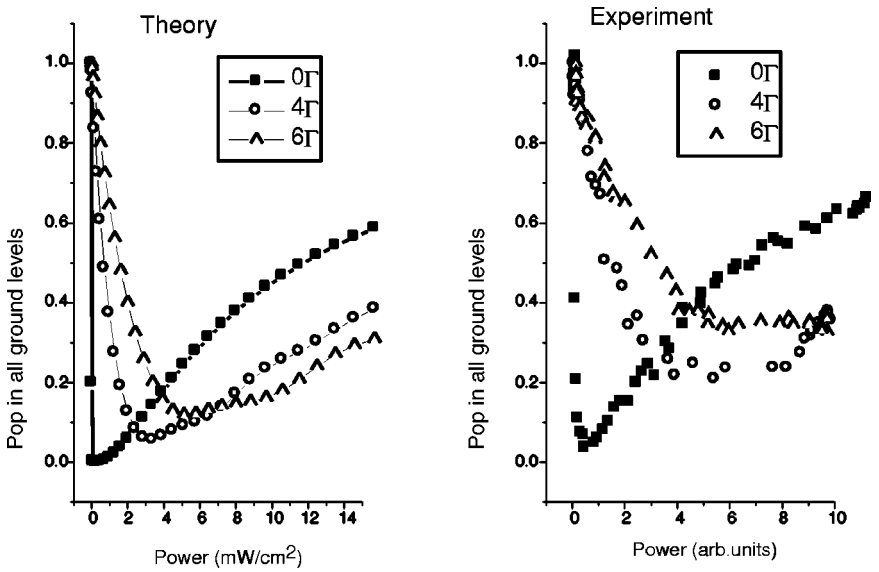

FIG. 8. The plots show the theoretical and experimental results for population in the ground level after a double transfer pulse of 40 μs for different detunings of the transfer light. The detunings are given in units of spontaneous decay frequencies. Note that the theory plot differs from that of Fig. 4(b) in that here, the population is summed over all ground states, not just $m_F=0$. Velocity selection has also been taken into account here, with an atomic source temperature of 5 μK.

theory. This is probably due to the fact that the model has assumed that any atoms that fall back to the ground level $F=4$ will not be in the dark state and will be immediately pumped out of the system. However, with a large detuning of the transfer light, the strength of coupling to the atom is reduced and so the pumping out of the dark state is slower. This means that in reality, there may be incoherent atoms left in the $F=4$ ground level which are not included in the model. This would yield the higher populations seen experimentally where incoherent atoms are also detected.

VII. ATOMIC SYSTEM WITH THE BEST EFFICIENCY

Confident of our model for adiabatic transfer we should examine the optimum atomic transition for efficiency of momentum transfer. A single $F=1\rightarrow F'=1$ transition would give us greater efficiencies than $F=4\rightarrow F'=4$ at a given intensity due to the larger eigenenergy separations as shown in Sec. III. To ensure the same momentum is imparted in each case, however, four $1\rightarrow 1'$ transitions would be needed instead of one $4\rightarrow 4'$ transition.[2]

To examine the relative merit of these systems, we can create two models for an imaginary atom with an atomic mass number of 100, a resonant wavelength of 800 nm, an excited level lifetime of 30 ns, and a saturation intensity of 2 mW/cm^2. Creating one model with only the levels $F=1$ and $F'=1$ and another with only $F=4$ and $F'=4$, we obtain the efficiency results shown by the solid curves in Fig. 9. From this, it is clear that for any given intensity four $1\rightarrow 1'$ transfers are much more efficient than one $4\rightarrow 4'$ transfer, particularly at lower intensities. Note that the dashed curves in Fig. 9 show the results of doing these calculations without taking velocity selectivity into account. The difference between the two systems is then less dramatic because velocity selection causes a bigger reduction in efficiency for one 100 μs pulse than for four 25 μs pulses.

Returning to the solid curves, which do include velocity selection, it appears for our experiment, where the intensity in the transfer beams is approximately 15 mW/cm^2, we would be much better off with a different atom. Rubidium 87 would be a good alternative to cesium as it has an $F=1\rightarrow F'=1$ transition in the $D1$ line. To check this idea, the model was re-run with the atomic data specific to rubidium. The result of four 25 μs transfers in rubidium is compared with one 100 μs transfer in cesium in Fig. 10, which includes velocity selection. The efficiencies are startlingly similar over a range of intensities and we see that rubidium would have no advantage for our experiment. The large difference between an ideal $1\rightarrow 1'$ system and rubidium arises from the fact that in rubidium the branching ratio on the $D1$ $F=1\rightarrow F'=1$ transition is only 1/6, whereas the idealized $1\rightarrow 1'$ system has the branching ratio as 1. The reduced branching ratio means that the coupling between the atom

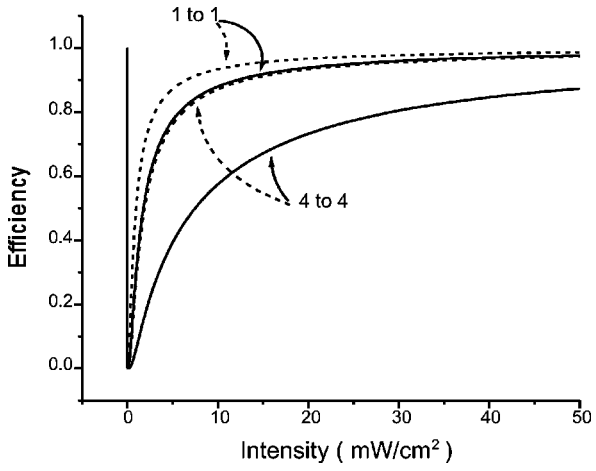

FIG. 9. The solid curves show the efficiencies as a function of intensity for an idealized $1\rightarrow 1'$ transition and an idealized $4\rightarrow 4'$ transition with velocity selection for a 5 μK source. The $1\rightarrow 1'$ transfer was performed four times (each of length 25 μs) so that it could impart the same momentum in the same time as the $4\rightarrow 4'$ transfer (of length 100 μs). The dashed curves show the same results but *without* the effect of velocity selection.

[2]Note that to impart the same momentum in each system, the AT light beams would have to have their directions reversed half way through each of the $1\rightarrow 1'$ double transfers, while those for the $4\rightarrow 4'$ system stay in the same direction.

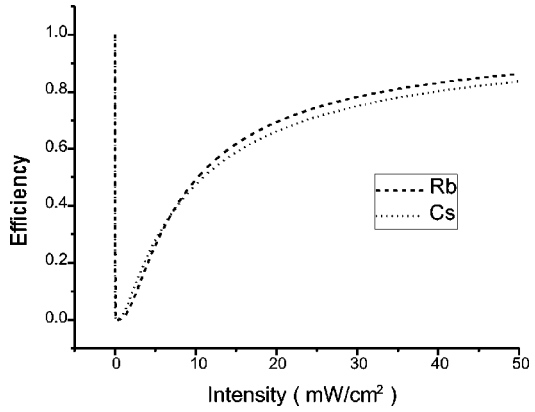

FIG. 10. Efficiencies as a function of intensity for rubidium (dashed line) and cesium (dotted line). The $1 \rightarrow 1'$ transfer was performed four times, each for 25 μs while the $4 \rightarrow 4'$ transfer was performed once for 100 μs. The effects of velocity selection were included in both cases, assuming an atomic source temperature of 5 μK.

and light field is reduced, thus lowering the efficiency. In cesium, the branching ratio on the $4 \rightarrow 4'$ transition is 5/12, so there is less of a reduction from the idealized system.

VIII. CONCLUSION

We have shown that an accurate prediction of the efficiency of adiabatic transfer in a multistate system requires a rigorous theoretical model. We have produced such a model and used it to show the contribution from different physical phenomena in transfer efficiency. In summary, to attain the highest transfer efficiency, the physical effects which should be considered are the following: first, the AT condition should be satisfied. This requires the transfer to be performed slowly and a relatively large energy gap between the dark eigenstate and its nearest coupled neighbor. The energy gap can be increased by using a lower-state system for the transfer, or by increasing the coupling strength between the atom and light field. The coupling strengths can be increased by using a higher laser power and also by choosing atomic levels with large transition amplitudes. Another effect to consider is the kinetic energy differences between the m_F states *within* the dark state as these will cause the state to be less dark for some velocities than others. This is the effect of velocity selectivity and its overall effect on transfer efficiency will depend very much on the particular velocity distribution of the atoms. It should also be remembered that off-resonant levels will play an increasingly important role, the closer they are to being on resonance with the transfer light. The validity of our model was demonstrated through its agreement with the experimental results and to finish, we used the model to predict the efficiencies of AT giving the same momentum transfer to different atoms, which can be important in matter wave optics.

ACKNOWLEDGMENTS

This work was supported by the U.K. EPSRC and the EU as part of the TMR ''Coherent Matter Wave Interactions'' network under Contract No. EBRFMRXCT960002.

[1] P. Marte, P. Zoller, and J. L. Hall, Phys. Rev. A **44**, 4118 (1991).
[2] J. Lawall and M. Prentiss, Phys. Rev. Lett. **72**, 993 (1994).
[3] L. S. Goldner, C. Gerz, R. J. C. Spreeuw, S. L. Rolston, C. I. Westbrook, W. D. Phillips, P. Marte, and P. Zoller, Phys. Rev. Lett. **72**, 997 (1994).
[4] P. Pillet, C. Valentin, R.-L. Yuan, and J. Yu, Phys. Rev. A **48**, 845 (1993).
[5] J. R. Kuklinski, U. Gaubatz, F. T. Hioe, and K. Bergmann, Phys. Rev. A **40**, 6741 (1989).
[6] P. D. Featonby, G. S. Summy, C. L. Webb, R. M. Godun, M. K. Oberthaler, A. C. Wilson, C. J. Foot, and K. Burnett, Phys. Rev. Lett. **81**, 495 (1998).
[7] A. Messiah, *Quantum Mechanics* (North-Holland, Amsterdam, 1962), Vol. 2, p. 754.
[8] G. Morigi, P. Featonby, G. Summy, and C. Foot, Quantum Semiclassic. Opt. **8**, 641 (1996).
[9] M. Weitz, B. C. Young, and S. Chu, Phys. Rev. A **50**, 2438 (1994).
[10] P. D. Featonby, G. S. Summy, J. L. Martin, H. Wu, K. P. Zetie, C. J. Foot, and K. Burnett, Phys. Rev. A **53**, 373 (1995).
[11] A. Aspect, E. Arimondo, R. Kaiser, N. Vansteenkiste, and C. Cohen-Tannoudji, J. Opt. Soc. Am. B **6**, 2112 (1989).