Multi-step adiabatic passage in a four-level 'tripod' atomic system

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As was recently shown experimentally by Bergmann and coworkers [1], adiabatic passage in a 'tripod' atomic level configuration (Fig. 1) allows one to coherently split full atomic population between two ground-state sublevels. In [1], a beam of metastable Ne atoms in the $(2p^5 3s)\ ^3P_0$ state, propagating along x axis, was incident on a combination of three laser beams: A pair of σ^+ and σ^--polarized beams counterpropagating along z axis, and a π-polarized beam propagating along y axis. The interaction of an atom with the π-polarized beam was delayed by shifting it along the x axis. An atom thus saw a synchronous pair of σ-polarised pulses, followed by a delayed yet overlapping π-polarised pulse (with wave vectors $\pm\mathbf{k}_\sigma$ and $\mathbf{k}_\pi$). The atomic states coupled via this pulse sequence are $|(2p^5 3s)\ ^3P_0, M=0\rangle$, $|(2p^5 3p)\ ^3P_1, M=0\rangle$, $|(2p^5 3s)\ ^3P_2, M=+1\rangle$ and $|(2p^5 3s)\ ^3P_2, M=-1\rangle$, hereinafter referred to as states 1, 2, 3^- and 3^+, respectively. An atom initially in state 1 with momentum $\mathbf{p}$ is adiabatically transfered into a coherent superposition of states $3^\pm$ with momenta $\mathbf{p}-\mathbf{k}_\pi \pm \mathbf{k}_\sigma$.

If one swaps polarizations of the σ-polarized beams, these states become coupled to momentum components of state 1 with momenta $\mathbf{p} \pm 2\mathbf{k}_\sigma$. Inverting also the time order of the σ and π-polarised pulses creates an optical-pulse sequence that adiabatically transfers the coherent superposition of *different* states $3^\pm$ into that of two momentum components of the *same* state 1. Using formulae for dark states in a tripod system [1], it can be shown that such 'inverse' pulse sequence indeed transfers 50% of atomic population into the said superposition of momentum substates of level 1 (in Raman-Nath approximation, assuming Rabi frequencies of the σ-pulses are equal). Another 50% end on levels 3^+ and 3^- (see below).

To verify these initial considerations, we simulated the atomic evolution numerically. The atomic motion in z and y directions was treated fully quantum-mechanically. In Figure 2, we plot the time dependence of the level populations (left panel) and of the atomic distribution over the z momentum (right panel). As is evident from this Figure, the final atomic population is equally split between level 1 and levels 3^+ and 3^-. Population of the excited level 2 stays negligible. It shows that the atomic dynamics caused by the 'inverse' pulse sequence indeed has a true nature of adiabatic passage. Its coherence may be demonstrated by plotting the spatial distribution of atomic population in level 1, which turns out to be a nearly perfect interference pattern.

Further, as was demonstrated by Chu and co-workers [2], having once created a coherent superposition of two states, momentum splitting may then be increased orders of magnitude using additional adiabatic-passage sequences. Inserting such sequences between the 'direct' and 'inverse' ones, arbitrary momentum splitting in the final state may be achieved.

[1] H. Theuer, R. G. Unayan, B. W. Shore and K. Bergmann, Optics Express **4**, 77 (1999)

[2] M. Weitz, B. C. Young, and S. Chu, Phys. Rev. Lett. **73**, 19 (1994)

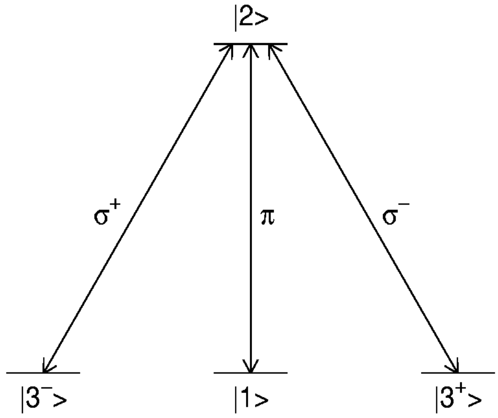

Figure 1: 'Tripod' level configuration [1].

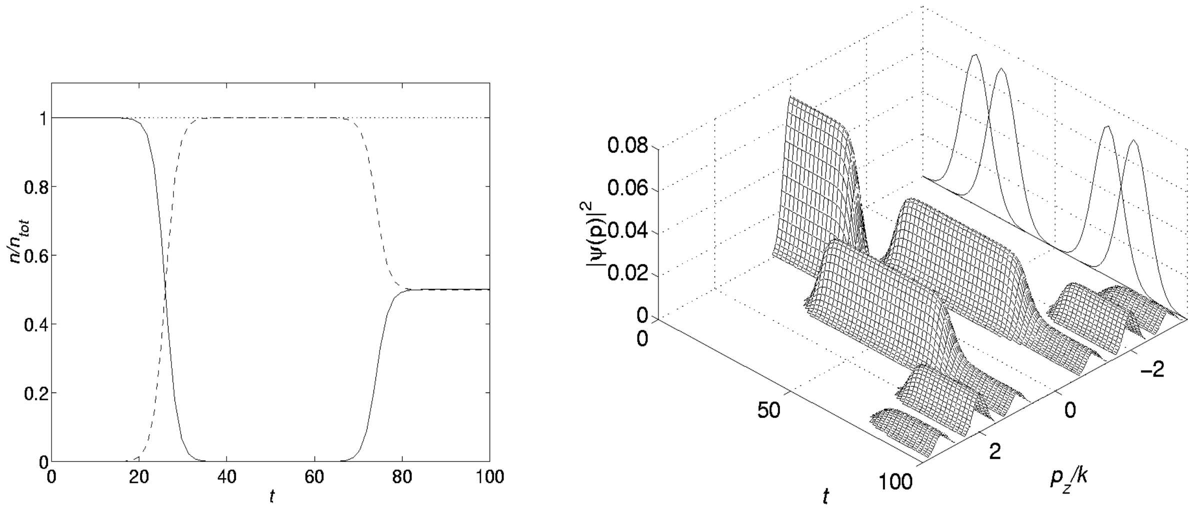

Figure 2: Atomic dynamics via numerical simulations. **Left**: Time dependence of the atomic population on level 1 (solid line), of the overall population on levels 3^+ and 3^- (dashed line), and of the total population on levels 1, 3^+ and 3^- (dotted line). The dotted line is indistinguishable from unity showing that population of the level 2 is negligible (in fact it stays within 10^{-3}). **Right**: Time dependence of the distribution over the z component of the atomic momentum. Contributions at $p_z = 0, \pm 2k$ are from state 1, those at $p_z = -k, +3k$ are from state 3^-, and those at $p_z = +k, -3k$ are from state 3^+. Synchronisation of the optical pulses is shown on the axes box wall as a guide to the eye. Time is measured in units of γ^{-1}, where γ is the lifetime of the exited atomic state. Numbers are chosen so as to match experimental conditions in [1]: $\gamma^{-1} = 19.2$ ns and $R = \hbar k_\sigma^2/2m\gamma \approx 3 \cdot 10^{-3}$. The initial width of the momentum distribution is $\Delta p = 0.4 k_\sigma$.