Three Level Atom Optics via the Tunneling Interaction

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(Dated: October 29, 2018)

Three level atom optics (TLAO) is introduced as a simple, efficient and robust method to coherently manipulate and transport neutral atoms. The tunneling interaction among three trapped states allows to realize the spatial analog of the stimulated Raman adiabatic passage (STIRAP), coherent population trapping (CPT), and electromagnetically induced transparency (EIT) techniques. We investigate a particular implementation in optical microtrap arrays and show that under realistic parameters the coherent manipulation and transfer of neutral atoms among dipole traps could be realized in the millisecond range.

The coherent coupling between two orthogonal states of a quantum system gives rise to oscillations of their probability amplitudes such as the Rabi oscillations of a two-level atom interacting with a laser field. When three instead of two levels are considered, the interaction gives rise to a much richer phenomenology. A clear example is the electric dipole interaction between a three-level atom and two laser modes, where a large number of techniques have been proposed and reported, such as the stimulated Raman adiabatic passage (STIRAP) method used to produce a complete population transfer between two internal quantum states of an atom or molecule, the modification of the optical properties of a medium by means of coherent population trapping (CPT), and electromagnetically induced transparency (EIT) phenomena. All these three-level optics (TLO) techniques have been intensively studied with applications ranging from quantum control of atoms and molecules, laser cooling, and slowing down light to a few meters per second to non-linear optics with few photons.

In this letter we propose several novel techniques for the coherent manipulation of atoms among trapped states coupled via tunneling. To illustrate the basic idea, let us start by considering two well separated dipole traps and one single atom in, say, the left trap. As soon as the two traps are approached and tunneling takes place, the probability amplitude for the atom to be in the left (right) trap oscillates in a Rabi-type fashion resembling the coupling of a two-level atom to a coherent field. This tunneling induced oscillation between the two traps can be used to coherently transfer atoms between traps and, in fact, it allows for a simple realization of quantum computation. However, this two-level technique is not very robust under variations of the system parameters and requires precise control of distance and timing. We will introduce here a set of tools analogous to the TLO techniques to efficiently and coherently manipulate and move atoms among traps. The basic elements will be three traps and a single atom, and the atomic external degrees of freedom will be controlled through the variation of the distance between each two traps. The proposed techniques do not need an accurate experimental control of the system parameters and they will be named three level atom optics (TLAO) techniques.

We will consider here arrays of optical microtraps where the dipole force of a red detuned laser field is used to store neutral atoms in each of the foci of a set of microlenses. We will make use of two specific features of these arrays: the possibility of individual addressing each trap and detecting whether a trap is occupied, and the independent displacement of columns or rows of microtraps. We assume here that we are able to initially store none or one atom per trap at will, as has been reported in single dipole traps and in optical lattices. Although we require only three traps the use of columns of traps has the advantage of doing several experiments in parallel.

The three in-line dipole traps are modeled as three piece-wise harmonic potentials of frequency $\omega_x$, and the neutral atom is assumed to be in the ground vibrational state of the left trap initially, while the other two traps are empty (Fig. 1). For simplicity the temporal evolution of the distance between each two traps has been modeled with a cosine function truncated at the minimum separation. Then, the approach and eventual separation of left and middle (middle and right) traps takes a time $t_{LM}^{MR}$ ($t_{MR}^{LM}$), while $t_{LM}^{MR}$ ($t_{MR}^{LM}$) is the time the traps remain at the minimum distance. The (unperturbed) three-level
system is composed of the vibrational ground states of all three traps, i.e., $|0\rangle_L$, $|0\rangle_M$, and $|0\rangle_R$, and the strength of the interaction between each two vibrational ground states is given (in the absence of the third trap) by the following tunneling "Rabi" frequency \[\Omega(d) = \frac{-1 + e^{(\alpha d)} [1 + \alpha d (1 - \text{erf}(\alpha d))]}{\sqrt{\pi} (e^{2(\alpha d)^2} - 1) / 2 \alpha d}\] (1)

where $\alpha d$ is the trap separation, and $\alpha^{-1} = \sqrt{R/m\omega_x}$ with $m$ denoting the mass of the neutral atom, erf(.) is the error function. The temporal shaping of $\Omega$ is realized by controlling the time dependence of $d(t)$. While Eq. (1) is useful to explore the analogies between TLO and TLAO, an exact treatment accounting also for couplings to excited vibrational states requires the integration of the Schrödinger equation. In what follows we will numerically integrate the 1D, and, eventually, the 2D Schrödinger equation to simulate the dynamics of the neutral atom in the three-trap potential.

A robust method to coherently move atoms among traps consists in extending the STIRAP technique \[\] to atom optics by using the tunneling interaction. The basic idea is to use the fact that one of the three eigenstates of the three level system involves only the ground states

$|D(\Theta)\rangle \equiv \cos \Theta |0\rangle_L - \sin \Theta |0\rangle_R$, \[\] (2)

where the mixing angle $\Theta$ is defined as $\tan \Theta = \Omega^{LM}/\Omega^{MR}$ with $\Omega^{LM}$ ($\Omega^{MR}$) denoting the tunneling "Rabi" frequency between left and middle (middle and right) traps. Following Eq. (2) it is possible to transfer the atom from $|0\rangle_L$ to $|0\rangle_R$ by adiabatically varying the mixing angle from $0^\circ$ to $90^\circ$, which means to approach and separate first the right trap to the middle one and, with an appropriate delay, the left trap to the middle one (Fig. 2a). This counterintuitive sequence moves the atom directly from $|0\rangle_L$ to $|0\rangle_R$ with an almost negligible probability amplitude to be in the middle trap ground state (Fig. 2b). The STIRAP signature is shown in Fig. 2c, where the transfer efficiency from $|0\rangle_L$ to $|0\rangle_R$ is shown as a function of the time delay between the two approaching processes. The plateau near the optimal delay indicates the robustness of the transfer process which also is very robust under variations of the tunneling parameters, i.e., of the maximum and minimum trap separation $d_{\text{max}}$ and $d_{\text{min}}$, and of $t_r$ and $t_i$ for each of the processes, provided that adiabaticity is maintained.

Additionally, the approaching sequence can be modified to create spatial superposition states with maximum atomic coherence, i.e., with $|c_0L c_0R\rangle = 1/2$, $c_0L$ ($c_0R$) being the probability amplitude to be in state $|0\rangle_L$ ($|0\rangle_R$). The basic idea is to adiabatically following state (2) from

![FIG. 2: (a) Approaching sequence for a STIRAP-like process, and (b) the corresponding ground state populations; $d^{LM}_{\text{max}} = d^{MR}_{\text{max}} = 6$, $d^{LM}_{\text{min}} = d^{MR}_{\text{min}} = 1.5$, $t_r^{LM} \omega_x = t_r^{MR} \omega_x = 150$, $t_i^{LM} \omega_x = t_i^{MR} \omega_x = 0$, and $t_{\text{delay}} \omega_x = 60$. (c) Transfer efficiency from $|0\rangle_L$ to $|0\rangle_R$ as a function of the time delay between the two approaching processes.](image)

![FIG. 3: (a) Approaching sequence for a CPT-like process; (b) Ground state and dark state populations, $p_{\text{dark}} = |\langle D(\Theta = \pi/2) | \psi(t) \rangle|^2$; $d^{LM}_{\text{min}} = 7$, $d^{MR}_{\text{min}} = 1.5$, $t_r^{LM} = t_r^{MR} = 200$, $t_i^{LM} = t_i^{MR} = 0$, $t_{\text{delay}} \omega_x = 120$ for the processes occurring before $t \omega_x = 600$. From $t \omega_x = 600$ on the parameters are the same as in the previous case except for $t_{\text{delay}} \omega_x = 0$.](image)
In the three-trap system we will inhibit the transition by applying an intense driving field to an adjacent transition. This approach and separate simultaneously the two extreme traps to the middle one (see Figs. 3(a) and 3(b) up to \( t\omega = 600 \)). The resulting state is the spatial equivalent to the well known dark state arising in the CPT technique \([2]\). To prove that this state is dark, i.e., that it can be decoupled from the tunneling interaction, we approach and separate simultaneously the two extreme traps to the middle one (see Figs. 3(a) and 3(b) from \( t\omega \) = 600 up to the end). Clearly, the atom remains in the dark state in spite of the tunneling interaction.

Superposition dark states are very sensitive to dephasing \([2]\), which means that they could be used in dipole trap systems to measure experimental imperfections such as uncorrelated shaking in the traps position and/or intensity fluctuations of the trapping lasers. Also, this robust coherent splitting of the atomic wavefunction between the left and the middle trap (see the plateau around \( t\omega = 180 \)). This effect, which is different from CPT and requires a combination of adiabatic and diabatic processes \([15]\), is possible through a complicated variation of the dressed level structure of the first excited states when approaching the traps.

There are two important practical points for the implementation of the TLAO techniques in optical microtrap arrays: (i) the trapping frequencies must be the same for all microtraps; and (ii) the approaching process has to be adiabatic. The use of a single laser that illuminates simultaneously all microlenses assures the identity of all microtraps even under intensity fluctuations of the laser. In particular, typical trapping frequencies for microtrap arrays of \(^{87}\)Rb atoms are \( 10^2 \)-\( 10^6 \) s\(^{-1} \) in the transverse directions and \( 10^4 \)-\( 10^5 \) s\(^{-1} \) along the laser beam direction.
FIG. 6: Three level atom optics for the first excited vibrational states: (a) transfer efficiency for STIRAP (dashed line: efficiency for the ground state STIRAP for the same parameters); and (b) population for the coherent splitting between $|1\rangle_L$ and $|1\rangle_R$: the parameters are (a) $t_L^{LM}\omega_x = t_R^{MR}\omega_x = 300$, $t_L^{LM}\omega_x = t_R^{MR}\omega_x = 0$; (b) $t_L^{LM}\omega_x = 550, t_R^{MR}\omega_x = 400$, $t_L^{LM}\omega_x = 75, t_R^{MR}\omega_x = 400$. In both cases $d_{max}\alpha = d_{max}\alpha = 9$ and $d_{min}\alpha = d_{min}\alpha = 1.5$.

which means that the traps can be adiabatically approached in the millisecond range or even faster by using optimization techniques . In addition, the spatial analogous of the CPT technique requires a precise control of the ratio between the two relevant "Rabi" frequencies. Fortunately, even in the presence of shaking in the microtraps position the ratio between the "Rabi" frequencies can be accurately controlled since mechanical vibrations give rise to a correlated shaking.

Throughout the paper we have assumed to be able to cool down the atom to the lower vibrational states of the traps. In fact, sideband cooling to a temperature below $1\mu K$ with a ground state population of 98.4% has been reported in optical lattices , with parameters very similar to the ones considered here. In this case, heating rates below $1\mu K/s$ have been estimated . In the presence of decoherence from heating, shaking and spontaneous scattering, fidelities above 98% can be expected for the ground-state TLAO techniques discussed here. However, it is worth to note again that all these techniques can be also applied to excited states. Note that the real trapping potentials differ from simple harmonic ones, but the three level atom optic techniques discussed here do not rely on the particular shape of the trapping potentials, provided the adiabaticity is maintained during the whole process of approaching and separating the traps.

Summarizing, we have introduced a set of robust and efficient techniques to coherently manipulate and transport neutral atoms based on three-level atom optics. These atom optics techniques correspond to the natural extension of the largely investigated STIRAP, CPT and EIT techniques used in quantum optics, with the interaction mediated via tunneling and controlled by the shaping of the process of varying the separation between the traps. The fact that three-level atom optics makes use of the tunneling interaction means some important differences with respect to the quantum optics case, such as the time scale of the processes being in the millisecond range, the absence of electric dipole rules, or the possible use of excited states. Applications to atomic interferometry and precision measurement have been briefly discussed and some practical considerations for the implementation in dipole trap arrays have been addressed. These three-level atom optics techniques are widely applicable also in other atom optics systems such as magnetic microtraps, optical lattices, and dipole and magnetic waveguides.

We would like to thank U. Poulsen for useful discussions and acknowledge financial support from MCyT (Spain) and FEDER (EC) under project BFM2002-04369, and from the DGR (Catalunya) under project 2001SGR-187, as well as from CESCA-CEPBA, the DFG (SPP Quantum Information Processing and SFB 407), and from ACQP (EC).

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