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Adiabatic population transfer in a multilevel system

P. Pillet, C. Valentin, R.-L. Yuan,* and J. Yu
Laboratoire Aimé Cotton, Centre National de la Recherche Scientifique II, Campus d'Orsay, Bâtiment 505,
91405 Orsay CEDEX, France

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We report an experimental observation of coherent population transfer in a multilevel system by adiabatic following through a trapped state. Raman transitions between ground-state sublevels are induced by two partially overlapping $\sigma^{\pm}$ polarized laser beams, tuned to the hyperfine transition $F=4\rightarrow F'=4$ of the cesium D_2 line. An efficiency of more than 50% is observed for the $m_F=+4\rightarrow m_F=-4$ population transfer. The influence of other excited hyperfine levels on the transfer efficiency is pointed out. The feasibility of the technique with counterpropagating laser beams is also demonstrated.

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Stimulated by new developments in laser cooling and manipulation of neutral atoms, atomic interferometry becomes currently a focus of research in atomic physics [1–4]. The realization of elements, such as lenses, mirrors, and especially beam splitters for atoms is obviously the key point for atomic interferometers and their applications. Elementary recoils in atom-laser interactions are used to split coherently an atomic beam into the two arms of a Mach-Zehnder interferometer [11]. Atomic interferometers have been built in the optical Ramsey-excitation geometry [2] and in the stimulated Raman transition scheme [3]. Atomic recoils in a standing wave (Kapitza-Dirac effect [5] and Bragg scattering [6]) present also attractive possibilities, although a large laser detuning is necessary to avoid any spontaneous emission. More recently, a novel process has been proposed to coherently deflect or split an incident atomic beam by a momentum transfer with adiabatic following in a multi-Zeeman-level system [7]. Such a transfer consists of maintaining the atomic system in a trapped state resulting from the Raman processes induced by two counterpropagating and partially overlapping $\sigma^{\pm}$ polarized laser fields. The nonabsorbing property of the trapped states allows the laser fields to operate on the atomic resonance without populating the excited state.

For a three-level Λ system ($|g_-\rangle$, $|g_+\rangle$, and $|e\rangle$), in the presence of $\sigma^{\pm}$ polarized laser fields, a nonabsorbing (NA) coherent superposition of the two ground states ($|g_-\rangle$ and $|g_+\rangle$) or trapped state can be built easily [7–9]:

$$|\mathrm{NA}\rangle=(\Omega_-/\Omega)|g_-\rangle-(\Omega_+/\Omega)|g_+\rangle\ ,$$

where $\Omega_{\pm}$ represents the Rabi frequency of the $\sigma^{\pm}$ polarized laser field and $\Omega=(\Omega_+^2+\Omega_-^2)^{1/2}$. Let us assume two $\sigma^{\pm}$ laser pulses, time-delayed and partially overlapped (σ^+ beam precedes the σ^- one, for instance). An atom initially prepared in $|g_+\rangle$ can be regarded as trapped in $|\mathrm{NA}\rangle$ ($\Omega_-=0$). As the σ^- component increases, the trapped state evolves with the change of the polarization. If the adiabatic condition is fulfilled, i.e., $\tau\gg\Omega_{\pm}^{-1}$ [τ is characterized by the full width at half maximum (FWHM) of the laser pulse duration], the atom will stay in the trapped state without any transition towards excited states and so without any spontaneous emission. At $t=+\infty$, the trapped state is switched to the $|g_-\rangle$ state ($\Omega_+=0$). The atomic population is so coherently transferred from $|g_+\rangle$ to $|g_-\rangle$. In the counterpropagating configuration, two elementary photon momenta $2\hbar k$ are also transferred to each atom [7]. The coherent population transfer has been demonstrated in a three-level Λ system in the Na_2 molecule [10] and discussed theoretically by several authors [11].

The rapid adiabatic following condition in NMR for a nonfree spin is given by $T_R\gg\tau'\gg\Omega_L^{-1}$, where τ' is the magnetic field variation time scale, Ω_L the Larmor precession frequency, and T_R the shortest relaxation time of the atomic internal coherence. In the optical domain, the generalization of such a process to a Bloch vector is straightforward. However, the optical coherence damping time is in general very short and imposes the use of very short laser pulses with very high peak power. The merit of the proposed method is actually to use trapped states with infinitively long relaxation time T_R.

In this Brief Report we present the experimental demonstration of the coherent population transfer in a multilevel system with adiabatic following in Raman processes induced by partially overlapping $\sigma^{\pm}$ laser fields. The adiabatic transfer occurs among the Zeeman components from $m_F=+4$ to $m_F=-4$ of the cesium ground hyperfine level $F=4$. Two features are presented in our experiments. First, the three-level Λ system is generalized to a $j\rightarrow j$ atomic transition, for which it is also possible to build nonabsorbing states. In such a system a $2j\hbar k$-momentum transfer can be expected in a counterpropagating laser configuration. We have considered the hyperfine transition $F=4\rightarrow F'=4$ of the cesium D_2 line ($6s\,^2S_{1/2}\rightarrow 6p\,^2P_{3/2}$, $\lambda=852.1$ nm). Second, the trapped state is no longer totally isolated in the presence of other hyperfine levels ($F'=3$ and 5) in the Cs excited state $6p_{3/2}$ and therefore presents a finite relaxation lifetime T_R. This effect has important influences on both the adiabatically criterion and the transfer efficiency. This point should be crucial for a large coherent deviation of an

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atomic beam using a multipassage configuration.

Our experimental setup is shown in Fig. 1. A detailed description of atomic beam and lasers can be found elsewhere [12]. The atoms escape from an oven (~120 °C) through a vertical 100-μm-wide slit. Five laser beams, denoted, respectively, as L_P, L_{T+}, L_{T-}, L_A, and L_D, cross the thermal atomic beam perpendicularly. L_P is provided by a feedback-stabilized Hitachi laser diode, frequency locked to the saturated absorption $F=4\rightarrow F'=5$ of the cesium D_2 line. L_P is σ^+ polarized and illuminates the atomic beam 120 mm away from the oven. The atomic population initially in a statistical mixing of the nine Zeeman components of the $F=4$ ground hyperfine level is optically pumped into the $m_F=+4$ Zeeman level. Then the atoms cross the transfer zone (Z_1), located at about 10 mm downstream. This zone consists of two $L_{T\pm}$ beams $\sigma^\pm$ polarized, tuned to the hyperfine resonance $F=4\rightarrow F'=4$. For studying the coherent population transfer, we consider first L_{T+} and L_{T-} propagating in the same direction. If L_{T+} precedes L_{T-} with partial overlapping between them, the atoms are transferred from the initial trapped state $m_F=+4$ corresponding to the σ^+ polarization to the final trapped state $m_F=-4$ corresponding to the σ^- one, without exciting the sublevels of the $F'=4$ hyperfine level during the whole process. The temporal as well as the spatial coherence of the two transfer beams are very important to maintain the Raman coherence during the process. The two laser beams $L_{T\pm}$ are splitted through a dual-beam polarizer (Rochon polarizer) from a single laser beam provided from a STC 50-mW laser diode, which is stabilized by optical injection from a feedback-stabilized Hitachi laser diode. The resulting linewidth is about 50 kHz. The two separated beams are superimposed again through a beam splitter prism cube, which is mounted on a microdisplacement stage providing a transverse displacement of L_{T+} relative to L_{T-} with a resolution better than 50 μm. A 100-mm-long Cs cell is used to improve the spatial homogeneity of the laser beams and to reduce the diffused light by spatially resolved saturated absorption. A cylindrical telescope is used to focus $L_{T\pm}$ on slit-shaped spots [width Δ (FWHM) of ~500 μm and height (FWHM) of ~2 mm] in the interaction zone Z_1. The total powers of L_{T+} and L_{T-} used in our experiments are typically 1.2 and 0.65 mW, respectively, which optimize the transfer efficiency for the given focalization of the laser beams. These nonidentical values obtained experimentally are explained by the nonsymmetrical shape of the laser pulses. Mean saturation parameters are evaluated to be $s_+=109$ and $s_-=59$, corresponding to the mean Rabi frequencies $\Omega_+=2\pi\times 39$ MHz$=7.47\Gamma$ and $\Omega_-=2\pi\times 29$ MHz$=5.56\Gamma$ ($\Gamma=2\pi\times 5.22$ MHz for the Cs D_2 line). For our thermal atomic beam ($\langle v\rangle\sim 280$ m/s) the interaction duration is in the order of $\tau=\Delta/v\sim 1.8$ μs$\gg 2\pi\Omega_\pm^{-1}$. The adiabatic condition is therefore well fulfilled.

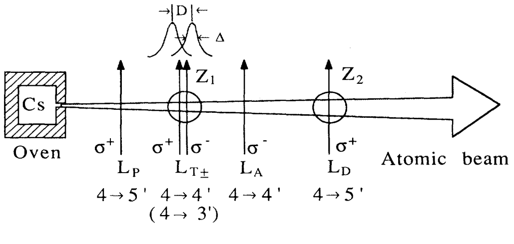

FIG. 1. Experimental setup.

The $m_F=-4$ population is analyzed by the L_A and L_D beams. The analyzing laser beam L_A has the same frequency and polarization as L_{T-}. It crosses the atomic beam about 10 mm away from the transfer zone. Its role is to destroy the atomic populations in all of the Zeeman components of the $F=4$ hyperfine level except that in the $m_F=-4$ sublevel. The presence of the L_A beam does not affect the adiabatic transfer signal. In the absence of adiabatic transfer, it is responsible for a small residual signal (see further), corresponding to the optical pumping of a few atoms in the $F=4$ and $m_F=-4$ level. A free-running Hitachi laser diode provides the detection laser beam L_D to measure the population in the $m_F=-4$ sublevel 50 mm downstream (Z_2). Its frequency is swept across the $F=4\rightarrow F'=5$ transition. Another detection is available over the transfer zone (Z_1) through the use of a charge coupled device (CCD) camera, giving a spatial resolution of the fluorescence induced by L_{T+} and L_{T-}.

The Earth's magnetic field is compensated for by three pairs of Helmholtz coils. A small homogeneous magnetic field (~100 mG) is applied along the laser beam propagation direction to dominate residual external fields and to stabilize the polarized atomic population. The Zeeman shift induced by this field is negligible (~35 kHz) compared to the linewidth of the Raman transition, given by the atomic beam transit time through the overlapping zone between L_{T+} and L_{T-}, $\Delta\nu\sim 1$ MHz.

The curve S_2 in Fig. 2 shows the population transfer efficiency measured in the case of the $F=4\rightarrow F'=4$ transition as a function of the displacement D, between the axes of L_{T+} and L_{T-}. D is measured in units of Δ and

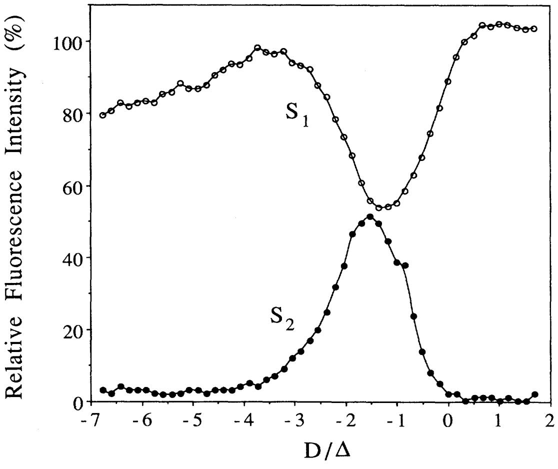

FIG. 2. The transfer efficiency (curve S_2) and the partial extinction of the L_T-induced fluorescence (curve S_1) as a function of the displacement D of L_{T+}, in the case of the $F=4\rightarrow F'=4$ transition.

its negative values correspond to the case where L_{T+} precedes L_{T-}. The transfer efficiency is given by the ratio of the measured fluorescence intensity to the total fluorescence obtained when L_{T+}, L_{T-}, and L_A are cut off. The polarization of the L_D beam is σ^+. The choice of this configuration does not affect significantly the fluorescence signal (compared, for instance, to σ^- polarization). The residual fluorescence in the absence of L_{T+} and L_{T-} (L_A on) is measured to be about 4% of the total fluorescence. The video signal from Z_1 is analyzed at the same time, giving the variation of the fluorescence intensity induced by L_{T-} as a function of D. The intensity is divided by the total fluorescence induced by L_{T-} in the absence of L_{T+} (S_1 in Fig. 2). A maximum transfer efficiency of 52% is obtained for $D \sim -1.5\Delta$. The partial extinction of the L_{T-}-induced fluorescence ($\sim 50\%$) correlates with the population transfer, indicating the coherent character of the process. As the transfer beam is detuned out of the resonance, the process is less efficient. For a detuning of 8Γ, the transfer efficiency decreases to half of that at the resonance.

To interpret our results, theoretical simulations have been carried out for the $F=4 \rightarrow F'=4$ transition in the cesium atom. The laser pulses used in the simulations are assumed to be of Gaussian form, with Rabi frequencies fitting approximatively our experimental conditions in the overlapping laser zone. The wave-function formalism is used in our calculations, in which the spontaneous emission from the excited states is taken into account by giving an imaginary part in the excited-state energies. An atom is considered to be lost from the coherent transfer process as soon as it emits a spontaneous photon. The theoretical results are given in Fig. 3. A maximum transfer efficiency of 90% is evaluated. The generalization of the present nine-level system from the three level Λ system does not reduce significantly the transfer efficiency, in the conditions of our experiment. As pointed out above, the $F'=4$ is not the only excited state. We have to consider the three hyperfine levels $F'=5$, 4, and 3 in the transfer process (the hyperfine splittings are 251 and 201 MHz, respectively). A calculation including them shows that the maximum transfer efficiency decreases to 55% (Fig. 3, curve *b*), in agreement with our experimental observations. The presence of spurious hyperfine levels is therefore an important source of leaks in the coherent transfer process. For the purpose of finding a more isolated trapped state, the cesium atom is, among the alkaline atoms, the best candidate with relatively large hyperfine splittings. Furthermore the D_1 line, with a 1167 MHz hyperfine splitting in the excited state, should provide a more ideal trapped state. A theoretical calculation gives us a maximum efficiency of 90% for the $F=4 \rightarrow F'=4$ transition of the D_1 line. The influence of the other hyperfine level ($F'=3$) is negligible in this case.

The same experiment has also been performed for the $F=4 \rightarrow F'=3$ transition of the D_2 line. We do not observe more than 15–20% transfer efficiency. For such a transition, the adiabaticity condition is more difficult to fulfill because of the strong asymmetry in the Clebsch-Gordan coefficients.

Finally, we have studied the counterpropagating $L_{T\pm}$ configuration. The direct observation of the coherent momentum transfer must be done preferably in a highly collimated atomic beam or in an atomic fountain. The expected $8\hbar k$-momentum transfer represents a velocity of 28 mm/s for cesium atoms, which results in a deviation angle smaller than 10^{-4} rad for a thermal beam. The transversal velocity Doppler effect shifts atoms out of the Raman transition resonance and only the atoms with the near-zero transversal velocity will be efficiently transferred. In our experiments, we observe a dark line on the L_{T-}-induced fluorescence centered along the propagating axis of the atomic beam, when L_{T+} is displaced to partially overlap L_{T-}($D \sim -1.5\Delta$) (Fig. 4). The width (FWHM) of the dark line is about 50 μm. The corresponding transversal velocities ± 0.45 m/s induce

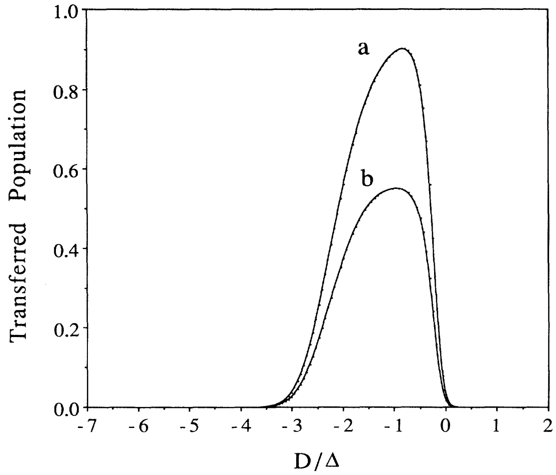

FIG. 3. Theoretically calculated transfer efficiencies as a function of D for $F=4 \rightarrow F'=4$ transition. (Curve *a*) Without consideration of other hyperfine levels. (Curve *b*) With consideration of other hyperfine levels, $F'=5$ and $F'=3$.

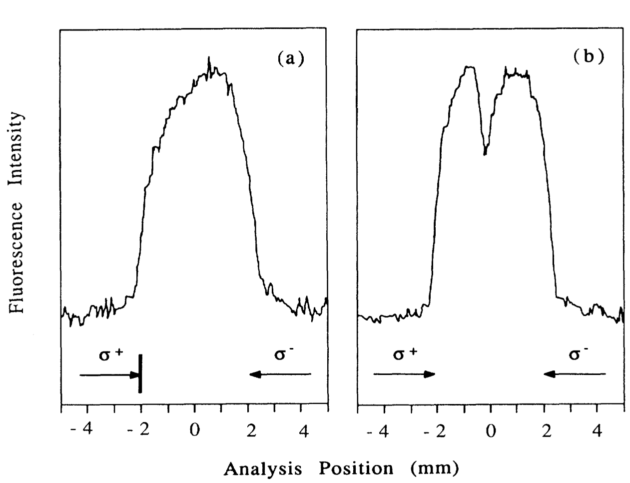

FIG. 4. Profile of the L_T-induced fluorescence in the laser propagation direction. (a) With L_{T-} only; (b) with counterpropagating L_{T+} and L_{T-} ($D \sim -1.5\Delta$)

Doppler shifts ±2×530 kHz, which is necessary to push atoms out of the Raman resonance ($\Delta\nu \sim 1$ MHz). The observation of the transfer signal in Z_2 cannot be done with a signal-to-noise ratio sufficiently well in this configuration. The zero-velocity transferred atoms have also received a $8\hbar k$-momentum transfer; even this is not directly measured.

In conclusion, the coherent population transfer has been observed in a multilevel system with an efficiency of more than 50% in the case of the $F=4 \rightarrow F'=4$ transition. Such an efficiency is limited by the presence of other hyperfine levels. The use of the D_1 line should improve the transfer process, allowing large momentum transfers efficiency in a multipassage configuration. The coherent transfer process can also be generalized to other laser-polarization configurations. An example is given by orthogonal linear polarizations, $\pi_x \perp \pi_y$, where an atomic population initially prepared in the $|m_F=0\rangle_x$ state will be adiabatically transferred into the $|m_F=0\rangle_y$ state. However, the σ^+-σ^- configuration remains the most suitable one in the applications to atomic optics and interferometry with the realization of atomic mirrors and beam splitters as pointed out in Ref. [7] and opens large and novel perspectives in these fields.

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*Permanent address: Department of Physics, Beijing Normal University, Beijing, China.

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