PHYSICAL REVIEW A **78**, 051603(R) (2008)

Radio-frequency-induced ground-state degeneracy in a Bose-Einstein condensate of chromium atoms

Q. Beaufils, T. Zanon, R. Chicireanu, B. Laburthe-Tolra, E. Maréchal, L. Vernac, J.-C. Keller, and O. Gorceix
Laboratoire de Physique des Lasers, CNRS UMR 7538, Université Paris 13, 99 Avenue J.-B. Clément, 93430 Villetaneuse, France

(Received 25 July 2008; revised manuscript received 26 September 2008; published 20 November 2008)

We study the effect of strong radio-frequency (rf) fields on a Bose-Einstein condensate (BEC) of chromium atoms, in a regime where the rf frequency is much larger than the Larmor frequency. We use the modification of the Landé factor by the rf field to bring all Zeeman states to degeneracy, despite the presence of a static magnetic field of up to 100 mG. This is demonstrated by analyzing the trajectories of the atoms under the influence of dressed magnetic potentials in the strong-field regime. We investigate the problem of adiabaticity of the rf dressing process and relate it to how close the dressed states are to degeneracy. Finally, we measure the lifetime of the rf dressed BECs and identify a rf-assisted two-body loss process induced by dipole-dipole interactions.

DOI: 10.1103/PhysRevA.78.051603 PACS number(s): 67.85.−d, 03.75.Mn, 32.10.Dk

When all magnetic substrates $|m\rangle$ of an atomic species ground state are nearly degenerate, it becomes possible to study new features related to the vectorial nature of the spin in the ground state of either multicomponent Bose-condensed [1] or Fermi-degenerate optically trapped gases [2]. These systems are known as spinor quantum gases. To explore these new features, it is important that differences in interaction energies between different total spin states are larger than their relative Zeeman energy, which requires magnetically shielded environments.

Up to now experiments on spin-1 [3] and spin-2 [4] spinor condensates were typically performed starting with atoms in the $|m=0\rangle$ magnetic state, with emphasis on spin dynamics and coherent oscillations between the spin components. Since spin dynamics is driven by spin exchange collisions, which do not modify the total spin angular momentum, one therefore works in a subspace insensitive to first order Zeeman effect, but the spinor ground state is not obtained [5]. A subspace insensitive to magnetic fields to the first-order is also used for quantum computing purposes with cold atoms in optical lattices, to reduce decoherence during quantum gate operations [6]. More generally, a very accurate control of the magnetic fields is required for precision measurements (e.g., atomic clocks use both magnetic shielding and a transition insensitive to the Zeeman effect to first order).

To ease the constraints on magnetic field control, we suggest to use strong off-resonant linearly polarized radio-frequency (rf) fields, to bring all Zeeman states to degeneracy despite a nonzero magnetic field. We demonstrate this idea by applying strong rf fields on optically trapped Bose-condensed chromium atoms. We analyze the trajectories of atoms in dressed magnetic potentials and we show that, as expected from [7], the Landé factor is modifed and can even be set to zero. At this point, all Zeeman states are degenerate. We show that the adiabaticity criterion for ramping up the rf power strongly depends on such degeneracy. Finally, we discuss inelastic losses measured in the dressed sample and attribute them to an exoenergetic rf-assisted dipolar coupling to higher partial waves.

Before describing our experimental results, let us give a physical insight into the modification of the atoms' eigenenergies by the rf field. As shown in [8] using first-order perturbation theory, when the rf frequency ω is much larger than the Larmor frequency $\omega_\perp$ the Landé factor g_J perpendicular to the rf field axis is modified by the rf dressing of the atom and is given by

$$g_J(\Omega) = g_J J_0\left(\frac{\Omega}{\omega}\right), \tag{1}$$

where $\Omega = g_J \mu_B B_{rf}/\hbar$ is the Rabi angular frequency, μ_B is the Bohr magneton, and J_0 is the zeroth-order Bessel function. As a result, the eigenenergies of the different $|m\rangle$ states dressed by rf, in the presence of a static magnetic field, read

$$E_m = m\mu_B g_J \sqrt{\left[B_\perp J_0\left(\frac{\Omega}{\omega}\right)\right]^2 + B_\parallel^2}, \tag{2}$$

where $B_\parallel$ and $B_\perp$ stand for the components parallel and perpendicular to the rf field.

When Ω is such that the Bessel function is zero, atoms are insensitive to transverse magnetic fields. We have derived a convenient picture of this effect from the classical dynamical equation of a spin in the presence of a rf field, $\vec{B}(t) = B_{rf}\cos(\omega t)\vec{z}$, which reads $d\vec{\mu}/dt = \frac{g_J\mu_B}{\hbar}\vec{\mu}\times\vec{B}(t)$. This equation has an analytical solution $\propto \cos[\frac{\Omega}{\omega}\sin(\omega t)]$, which, when time averaged, leads to $\langle\mu_x\rangle$, $\langle\mu_y\rangle \propto J_0(\frac{\Omega}{\omega})$, where $\langle\mu_x\rangle$ and $\langle\mu_y\rangle$ are the time-averaged values of $\vec{\mu}$ perpendicular to the rf field. In the presence of a small bias field $B_\perp\vec{x}$ perpendicular to $\vec{B}_{rf}$ the average energy of a classical spin is $\langle\mu_x\rangle B_\perp \propto g_J(\Omega)\mu_B B_\perp$. In this picture, the effect of rf on g_J can be seen as resulting from a sinusoidal modulation of the frequency of precession of the atoms. As in many other systems (frequency modulation of a laser, sinusoidal diffraction of light or matter waves, modulation of the depth of an optical lattice [8], modulation of the eigenenergies of Rydberg atoms [9]), this results in the occurrence of Bessel functions.

The rf renormalization of g_J described in [7] was first probed using microwave spectroscopy [10] and through the modification of spin-exchange collisions between Rb and Cs atoms [11]. In both these experiments, the magnetic fields were in the micro-Gauss range. Here, we observe the reduc-

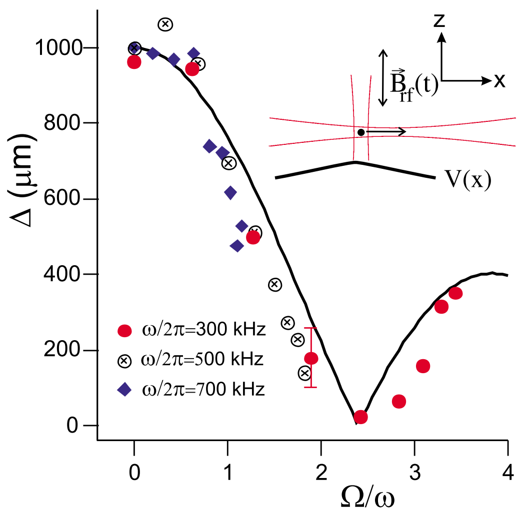

FIG. 1. (Color online) Displacement Δ of the dressed BEC after 35 ms of drift in the horizontal trap, relative to the displacement of $|m=0\rangle$ atoms under similar conditions, as a function of rf power, for three different rf frequencies. Line: $\Delta_{max}|J_0(\frac{\Omega}{\omega})|$. The relative uncertainty on the horizontal axis is about 10%. The error bar gives (as in Fig. 2) the typical statistical uncertainty. Inset: sketch of the experimental setup. The BEC is formed at the intersection of two dipole traps. When the vertical one is switched off, atoms drift in the horizontal trap and are accelerated by the magnetic potential $V(x)$.

tion of magnetic forces on an optically trapped Bose-Einstein condensate of chromium atoms, in the presence of magnetic fields up to 100 mG. We therefore greatly reduce the sensitivity of atoms to magnetic fields up to a value easily controlled by experimentalists, even without magnetic shielding.

Our recipe to produce ^{52}Cr Bose-Einstein condensates (BECs) is described in [12]. Forced evaporation is performed in a crossed optical dipole trap, and BECs are produced with typically 10 000 atoms in the absolute ground state $|S=3, m=-3\rangle$, in about 14 s. At this stage, the magnetic field is 2.3 G.

After BEC has been reached, we adiabatically recompress the optical dipole trap (then, the chemical potential is about 4 kHz) and reduce the magnetic field at the BEC position to a value of 50 mG, corresponding to a Larmor frequency of 85 kHz. We characterized the magnetic field at the atoms' position to a precision of 2 mG by rf spectroscopy. In addition, we also measure a magnetic field gradient of $b'=0.25$ G/cm along the axis of the horizontal dipole trap. After the magnetic field has reached its final value, atoms are released into the horizontal optical trap by suddenly removing the vertical trapping beam. The atoms are then accelerated by the magnetic field gradient b'. Atoms in the $|m=-3\rangle$ state experience an anticonfining potential $V(x)=-mg_J\mu_B b'|x|$, and they are expelled from the center of the trap. Due to the radial confinement of the dipole trap, the motion of the atoms is channeled in one direction. In fact, the BEC is not produced exactly at the waist of the trapping laser, so that atoms also experience a force due to the gradient of the dipole longitudinal potential (see inset in Fig. 1). We therefore measure the displacement of the atoms, relative to the displacement of atoms in $|m=0\rangle$ under similar conditions. This additional longitudinal displacement $\Delta(t)$ of the BEC after a time t provides a measurement of $g_J(\Omega)$ since $\Delta(t)=\frac{1}{2}\frac{mg_J(\Omega)\mu_B b'}{M}t^2$, where M is the atom mass. Using a BEC enables us to precisely measure $\Delta(t)$ for "long" delay without being disturbed by substantial expansion of the cloud.

Radio-frequency fields are applied to the atoms using a 150-W rf amplifier driving an 8-cm-diameter, eight-turn coil, located 4 cm away from the atoms. The rf frequency is larger than all Larmor frequencies at any given position of the atomic cloud trajectory. When a sufficiently strong rf field is applied, the trajectory of the atoms is modified as they travel through rf-dressed adiabatic potentials. Figure 1 represents Δ(35 ms) as a function of Ω/ω for three different frequencies ω. For this experiment, we ramped the rf in 1 ms up to its final value Ω. The change in position as the rf power is modified is a signature of the modification of g_J. For each value of ω, the Rabi frequency of the atoms was precisely calibrated by measuring Rabi oscillations in a magnetic field $\vec{B}_0 \| \vec{x}$ with a Larmor frequency $\omega_0=\omega$. All data points lie close to the same universal curve corresponding, for $\Omega/\omega<2.4$, to Eq. (1). There is no adjustable parameter on the horizontal axis, and the amplitude of the Bessel function is set by Δ_{max}, the displacement of the atoms when the rf is off. Up to $\Omega/\omega=2.4$, at which point $g_J(\Omega)=0$, our data are therefore consistent with theoretical predictions.

For $\Omega/\omega>2.4$, the agreement breaks down. Instead of changing sign, as predicted by Eq. (1), g_J remains positive and rises again. To understand this issue, we refer to Fig. 2(a), where the eigenenergies E_m [see Eq. (2)] of the dressed states are qualitatively represented. As expected from Eq. (1), when the Bessel function approaches zero, all eigenstates become nearly degenerate. There is nevertheless an avoided crossing associated with the presence of a small bias field component $B_\|$ parallel to the rf field. The fact that we are not able to reverse magnetic forces on the atoms, evidenced in Fig. 1, indicates that we are adiabatic while reaching this avoided crossing, whereas one needs to be fully diabatic to follow the Bessel-function curve. We therefore expect that the experimental points in Fig. 1 should follow the absolute value of the Bessel function, as we observed.

To improve our understanding of the adiabaticity issues, we performed additional experiments. We raise the rf power in a much shorter time (20 μs) and let the dressed atoms expand in the magnetic gradient. The atoms remain in one eigenstate for $\Omega/\omega<2.4$, but when the avoided crossing is reached, the BEC is projected on a superposition of all dressed states. We plot in Fig. 2(b) the position of the two extreme dressed states after 45 ms of drift in the horizontal trap. One follows the Bessel function, the other its absolute value. This indicates that for a 20-μs ramp-up time, the crossing of the point at 2.4 is not adiabatic. To be more quantitative, we performed the following experiments, described in Fig. 3. We apply the rf field to the atoms initially polarized in $|m=-3\rangle$ and study how the switch-off time impacts on the probability of recovering the initial state. The rf power is ramped up in 1 ms, stays up for $(1-\tau)$ ms, and is ramped down in τ. We switch off the vertical trapping beam and perform a Stern-Gerlach experiment: the atoms expand in the horizontal dipole trap, and the magnetic field gradient separates the different $|m\rangle$ states. We plot in Fig. 3(a) the

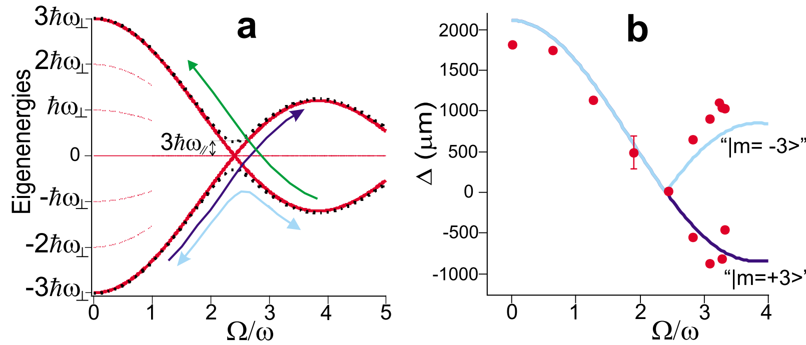

FIG. 2. (Color online) (a) Sketch for adiabaticity issues. We plot the eigenenergies of states adiabatically connected to the different Zeeman states, when the longitudinal field $B_\parallel$ is null (red) or not (dotted black). The arrows represent in light blue the dressing and undressing corresponding to the fully adiabatic process and in dark blue (green) a fully diabatic dressing (undressing) process. (b) Similar results as in Fig. 1 (with $\omega/2\pi=300$ kHz), except that the rf power is ramped up in 20 μs instead of 1 ms. For $\Omega/\omega>2.4$ many dressed states are populated and we only represent the displacement of the extreme ones.

probability of remaining in the $|m=-3\rangle$ state after the rf ramp, as a function of τ, at a rf frequency of 300 kHz. If $\tau>100$ μs, the atoms come back to the initial state, showing that the process is adiabatic, as represented by the light blue arrow in Fig. 2(a). When τ is small, instead of coming back to the initial $|m=-3\rangle$ state, we populate mostly $|m=+3\rangle$, as illustrated in the false color pictures of Fig. 3 (the variation of the total absorption signal is due to the m-state dependence for a short circularly polarized imaging pulse). This indicates that on this time scale, crossing the $\Omega/\omega=2.4$ point is diabatic. This process is represented by the green arrow in Fig. 2(a).

In Fig. 3(b), we show the influence of $B_\parallel$ on the adiabaticity time scale. The rf is ramped up in 20 μs to reach $\Omega/\omega=3.25$, and we measure for different values of $B_\parallel$ the population of the atoms following the adiabatic trajectory [upper branch in Fig. 2(b)]. We can qualitatively interpret the influence of $B_\parallel$ on the adiabaticity time scale using a Landau-Zener criterion $\frac{dE}{\hbar dt}\approx\omega_\parallel^2$ where $\omega_\parallel$ is the Larmor angular frequency associated with $B_\parallel$, $\frac{dE}{dt}\approx\frac{3\hbar\omega_\perp}{\Delta t}$, and $\Delta t=20$ μs the rf rising time. A good adiabaticity is then expected for $B_\parallel>20$ mG, which is consistent with our measurements.

The breakdown of adiabaticity as illustrated in Figs. 2 and 3 is thus a signature of all dressed eigenstates getting close to degeneracy. On the other hand, in the prospect of using this rf dressing technique to reach the ground state of spinor systems, the fact that increasing the rf power sufficiently slowly is reversible (see Fig. 3) is important: to remain in the ground state of the many-body system, it is important to make sure that dressing and undressing of the atoms are indeed adiabatic, at least in the single-particle limit. In practice, we do observe that a polarized BEC is recovered with no substantial heating after having interacted with the rf.

In a spinor BEC one has to consider the interaction between the particles. In this prospect, we first investigate the question of the collisional stability of the BEC when dressed by rf. We performed measurements of the BEC lifetime in the crossed optical dipole trap. We observe density-dependent nonexponential decay, and we report in Fig. 4 the inverse of the decay rate at short time, Γ_0, as a function of the rf power. Although lifetimes as small as 50 ms are obtained, the trap frequencies are on the order of 300 Hz and the chemical potential is 4 kHz. This ensures thermal equilibrium as the dressed BEC decays.

As the atoms are in the lowest state of energy of their manifold of rf-dressed states, the inelastic process necessarily implies a coupling to a lower manifold. Such a coupling can only result from the spin-dependent part of the interparticle potential, which is necessarily the magnetic dipole-

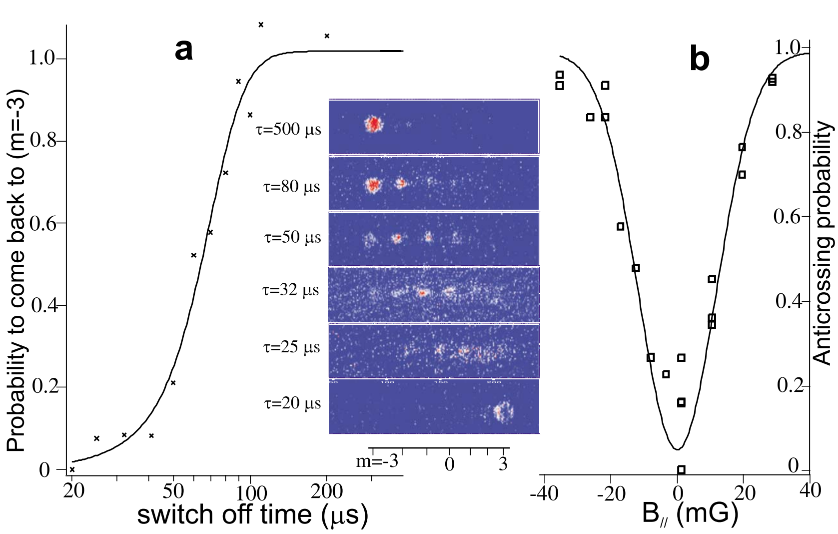

FIG. 3. (Color online) (a) Measurement of the probability of recovering the initial $|m=-3\rangle$ state after rf dressing, as a function of the switch-off time τ for $\Omega/\omega=2.8$. Absorption pictures after 35 ms of expansion in the horizontal dipole trap, in the presence of the magnetic field gradient, for different values of τ. (b) Probability for an adiabatic dressing process as a function of $B_\parallel$. The rf is switched on in 20 μs and applied for 45 ms with $\Omega/\omega=3.25$. Lines are guides for the eyes.

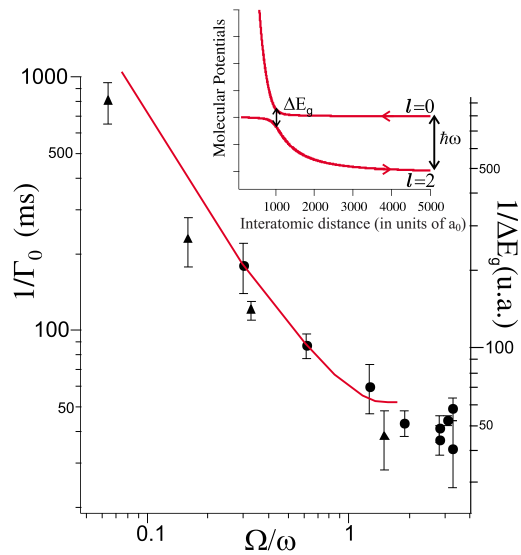

FIG. 4. (Color online) Left: inverse of the experimental BEC decay rate at short time for different rf powers at rf frequencies of 300 kHz (solid circles) or 500 kHz (triangles). Right (solid line): inverse of the calculated gap ΔE_g. Inset: molecular potentials of two adjacent manifolds with $l=2$ and $l=0$ to illustrate our model for losses.

dipole potential since there are no hyperfine interactions for ^{52}Cr. In order to get an insight into the loss mechanism, we numerically solved the problem of two spin-1/2 atoms in $|m=-1/2\rangle$ dressed by rf in the strong-field regime, in the presence of dipole-dipole interactions. Such atoms are colliding in the state $|S=1, m_S=-1, l=0, m_l=0\rangle$—where l defines the incoming partial wave—belonging to a given manifold. We find that an avoided crossing opens with rf power between the molecular adiabatic potentials corresponding to this state and to the state $|S=1, m_S=-1, l'=2, m_l'=-1\rangle$ belonging to the nearest lower manifold. The avoided crossing occurs at a distance R_c such that the centrifugal barrier energy $\frac{l'(l'+1)\hbar^2}{2\mu R_c^2}\approx\hbar\omega$, with $\mu=M/2$. Typically, $R_c\approx 900a_0$, and the attractive molecular potential does not come into play (see the inset of Fig. 4). The gap ΔE_g is proportional to the dipole-dipole coupling strength V_d, and for large rf power, $\Delta E_g\approx V_d(R_c)$. Pairs of atoms transferred in the lower manifold by this mechanism acquire a kinetic energy $\hbar\omega$ and are expelled from the trap.

This mechanism reminds us of dipolar relaxation *without rf*, for atoms in the stretched state of *maximum* energy in a static magnetic field B_{eq}. Then an avoided crossing with a gap $\approx V_d(R_d)$ opens between the potentials of $|S=1, m_S=1, l=0, m_l=0\rangle$ and $|S=1, m_S=0, l'=2, m_l'=1\rangle$ at a distance R_d such that $\frac{l'(l'+1)\hbar^2}{2\mu R_d^2}=g_J\mu_B B_{eq}$. Therefore, the two-body loss parameter that we expect for this rf-assisted mechanism is on the same order of magnitude as K_2^{rel}, the two-body loss parameter for dipolar relaxation in a static field $B_{eq}\approx\frac{\hbar\omega}{g_J\mu_B}$. Given the known value for K_2^{rel} [13] and our typical BEC density, a typical lifetime of a few tens of ms is expected at large rf power. Although a full quantitative analysis is beyond the scope of this paper, we represent in Fig. 4 the evolution of the gap we have calculated as a function of rf power. A saturation at $\Omega/\omega\approx 2$ is obtained, as for our measured losses. At larger power, ΔE_g starts decreasing again, but other gaps open, coupling the initial state to even lower manifolds.

Controlling the magnetic-state degeneracy would be very useful for many applications. We have already stressed the relevance of this issue to spinor physics. The use of strong rf fields to achieve this goal reduces significantly the BEC lifetime in the case of chromium due to strong dipole-dipole interactions. However, we expect much larger lifetimes for atomic species with a smaller magnetic moment. For some applications, a complete three-dimensional effective magnetic shielding may be required. We are currently theoretically investigating this issue by considering the interaction of atoms with two perpendicular rf fields at two different frequencies.

LPL is Unité Mixte (UMR 7538) of CNRS and of Université Paris 13. We acknowledge financial support from Ministère de l'Enseignement Supérieur et de la Recherche and IFRAF (Institut Francilien de Recherche sur les Atomes Froids). We thank Pr. Ennio Arimondo for stimulating discussions.

[1] Tin-Lun Ho, Phys. Rev. Lett. **81**, 742 (1998).
[2] S. Capponi *et al.*, Phys. Rev. A **77**, 013624 (2008).
[3] A. E. Leanhardt, Y. Shin, D. Kielpinski, D. E. Pritchard, and W. Ketterle, Phys. Rev. Lett. **90**, 140403 (2003); H. Saito, Y. Kawaguchi, and M. Ueda, *ibid.* **96**, 065302 (2006).
[4] H. Schmaljohann *et al.*, Phys. Rev. Lett. **92**, 040402 (2004), M.-S. Chang *et al.*, *ibid.* **92**, 140403 (2004); T. Kuwamoto, K. Araki, T. Eno, and T. Hirano, Phys. Rev. A **69**, 063604 (2004); M. H. Wheeler, K. M. Mertes, J. D. Erwin, and D. S. Hall, Phys. Rev. Lett. **93**, 170402 (2004).
[5] Recently, spontaneous symmetry breaking was observed in a spinor Bose condensate, as the quadratic Zeeman shift was rapidly driven below the spin-dependent interatomic interactions; see L. E. Sadler *et al.*, Nature (London) **443**, 312 (2006).
[6] M. Anderlini *et al.*, Nature (London) **448**, 452 (2007).
[7] S. Haroche, Ph.D. thesis, Université Paris 6, 1971.
[8] C. Cohen-Tannoudji, J. Dupont-Roc, and G. Grinberg, *Atom-Photon Interactions: Basic Processes and Applications*, Wiley Science, New York, 1998.
[9] P. Pillet, R. Kachru, N. H. Tran, W. W. Smith, and T. F. Gallagher, Phys. Rev. A **36**, 1132 (1987).
[10] S. Haroche *et al.*, Phys. Rev. Lett. **24**, 861 (1970).
[11] S. Haroche and C. Cohen-Tannoudji, Phys. Rev. Lett. **24**, 974 (1970).
[12] Q. Beaufils *et al.*, Phys. Rev. A **77**, 061601(R) (2008).
[13] S. Hensler *et al.*, Appl. Phys. B: Lasers Opt. **77**, 765 (2003).