CHIN. PHYS. LETT. Vol. 27, No. 7 (2010) 074202

Adiabatic Passage Based on the Calcium Active Optical Clock *

XIE Xiao-Peng(解晓鹏), ZHUANG Wei(庄伟), CHEN Jing-Biao(陈景标)**

Institute of Quantum Electronics, and State Key Laboratory of Advanced Optical Communication System & Network, School of Electronics Engineering & Computer Science, Peking University, Beijing 100871

(Received 4 January 2010)

We propose a new application of the optical adiabatic passage effect for the excitation of a thermal atomic beam, which will be used in the calcium active optical clock to produce population inversion. A comparison between the optical adiabatic passage effect and the Rabi π pulse is investigated, 99% of the calcium atoms in the atomic beam that has a wide velocity distribution will be excited to the upper state for population inversion using the adiabatic passage, while 76% at most will be excited to the excited state using the π pulse with suitable parameters.

PACS: 42.50.−p, 39.10.+j, 32.80.Qk DOI: 10.1088/0256-307X/27/7/074202

For many purposes it is desirable to produce samples of atoms or molecules whose the population resides almost entirely in a particular excited state. There are two well-known procedures which can, in principle, produce complete population transfer in an ensemble of two-state atoms or molecules,[1] one is the π pulse that makes use of Rabi population oscillations, and the other one is the adiabatic passage.

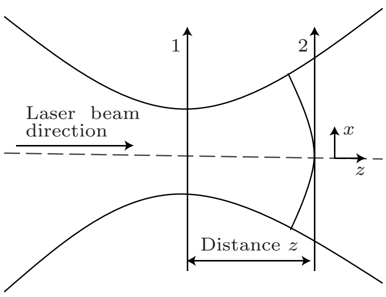

Fig. 1. The laser beam and two atomic trajectories, (1) resulting in Rabi oscillations, (2) resulting in an adiabatic passage.

The pioneering works concerning adiabatic passage were performed in nuclear magnetism to achieve population inversion of a spin system.[2] In 1968, it was suggested that this technique could also be used in the optical regime,[2] and the first application of this method in the optical domain was realized in Ref. [4] to invert the population of NH_3 molecules. Ever since, a multitude of different adiabatic passage techniques have been proposed and successfully realized. Examples can be found in atoms and molecules,[5,6] the population of selected Rydberg states,[7] in atomic de Broglie wave optics,[8,9] and subrecoil laser cooling.[10,11]

In this Letter, we will investigate another new application for population inversion in the atomic beam, which will be used in the calcium active optical clock[12] to produce population inversion. As shown in Fig. 1, Rabi oscillations will be present when the Ca atomic beam crosses the laser beam right at the laser waist. The adiabatic passage will take place when the Ca atoms cross the laser beam well away from its waist,[13−15] where the curvature of the wavefront causes a Doppler shift.

For the thermal Ca atomic beam, which has a wide velocity distribution, at most 76% of the atoms will be excited to the upper state using the Rabi population oscillations in principle, which is sensitive to the laser power and interaction time. However, the adiabatic passage will obtain almost 99% of the atoms excited to the upper state theoretically. What is more important is that the latter excitation process is very robust because it does not critically depend on the exact value of the laser intensity and the specific shape of the frequency chirp.

Then we will use the related theory work performed by Kroon *et al.*[13] to give some numerical analysis for the two procedures based on the Ca active optical clock. The ${}^1S_0$–${}^3P_1$ transition ($\lambda = 657\,\mathrm{nm}$)of the Ca atom involved in the active optical clock has a lifetime of 0.4 ms,[16] which is much longer than the interaction time between the atom and the laser beam; we will ignore all the effect caused by spontaneous decay of the excited state.

When the Ca atomic beam crosses the laser beam($\lambda = 657\,\mathrm{nm}$) right at the waist, considering the simplest model of a single-mode laser beam interaction with a two-level atom,[13] we have

$$\frac{dc_a(t)}{dt} = \frac{i}{2}R_{ab}e^{-i\Delta\omega t}c_b(t), \tag{1}$$

$$\frac{dc_b(t)}{dt} = \frac{i}{2}R_{ba}e^{+i\Delta\omega t}c_a(t), \tag{2}$$

where c_a and c_b are the probability amplitudes of finding an atom in the lower state and upper state respectively, $\Delta\omega = \omega_b - \omega_a - \omega$ is the frequency detuning of the atom and laser, in the rotating-wave approximation, $|R_{ab}| = |-\langle a|\mu_z|b\rangle E/\hbar| = |R_{ba}| = R$ is the

*Supported by the National Basic Research Program of China under Grant No 2005CB724500, the National Natural Science Foundation of China under No 10874009, and Open Research Found of State Key Laboratory of Precision Spectroscopy (East China Normal University).
**Email: jbchen@pku.edu.cn

Rabi frequency, where μ_z is the dipole moment along the z axis. When considering the Gaussian profile of the electric field amplitude of the laser beam, the Rabi frequency R will be time dependent. By selecting suitable parameters one will obtain the solution of Eqs. (1) and (2) numerically for atoms with different velocities. Population of the upper state level $|c_b(t)|^2$ is also a function of the interaction position $x = vt$, as shown in Fig. 2, for different velocities the probabilities $|c_b|^2$ that atoms are excited to upper states after the interaction zone are different, and the probability $|c_b|^2$ is determined by the laser power, the size of the laser waist, and the atom velocity.

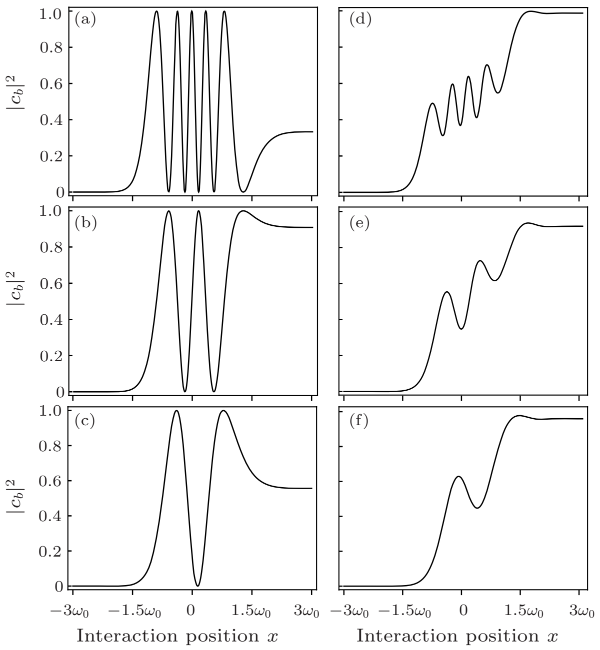

Fig. 2. Population of the upper state level $|c_b|^2$ as a function of the interaction position x in the Gaussian laser beam. The left-side is the Rabi oscillation for different velocities, (a) $v = 400\,\mathrm{m/s}$ (b) $v = 800\,\mathrm{m/s}$ (c) $v = 1200\,\mathrm{m/s}$ and the laser power is $P = 50\,\mathrm{mW}$, the waist is $w_0 = 1\,\mathrm{mm}$. The right-side is the adiabatic passage for different velocities, (d) $v = 400\,\mathrm{m/s}$ (e) $v = 800\,\mathrm{m/s}$ (f) $v = 1200\,\mathrm{m/s}$, the distance from the waist is $z = 2\,\mathrm{m}$, and the power is $P = 10\,\mathrm{mW}$, the waist is $w_0 = 0.5\,\mathrm{mm}$, w is the laser radius at the distance z.

When atoms cross the laser beam at a distance from the laser waist, angular frequency of the electric field will also be time dependent, e.g., by sweeping the frequency of the laser field, the phase factor of the field is given by $\exp[i\int^t \omega(t')dt']$, resulting in a modified set of differential equations:[13]

$$\frac{dc_a(t)}{dt} = \frac{i}{2}R_{ab}c_b(t)\exp\Big[-i\int_{-\infty}^{t}\Delta\omega(t')dt'\Big], \quad (3)$$

$$\frac{dc_b(t)}{dt} = \frac{i}{2}R_{ba}c_a(t)\exp\Big[+i\int_{-\infty}^{t}\Delta\omega(t')dt'\Big], \quad (4)$$

where $\Delta\omega(t) = \omega_b - \omega_a - \omega(t)$ is the frequency difference, and we consider the Doppler shift caused by the curvature of the wave fronts:

$$\Delta\omega_D(t) = -\Big(\frac{v^2\omega}{c\rho}\Big)t \quad (5)$$

with a constant rate of change proportional to v^2, where ρ is the radius of the curvature of the wave front at distance z. Using Eq. (5) we obtain a time-dependent frequency difference

$$\Delta\omega(t) = \omega_b - \omega_a - \omega - \Delta\omega_D(t). \quad (6)$$

If we assume that

$$\Delta\omega(t) = \Delta\dot{\omega}(0)t \quad (7)$$

we can obtain the numerical solution for Eqs. (3) and (4), as shown in Fig. 2. It is surprising that almost all the atoms will be excited to the upper level after the interaction zone despite having different velocities.

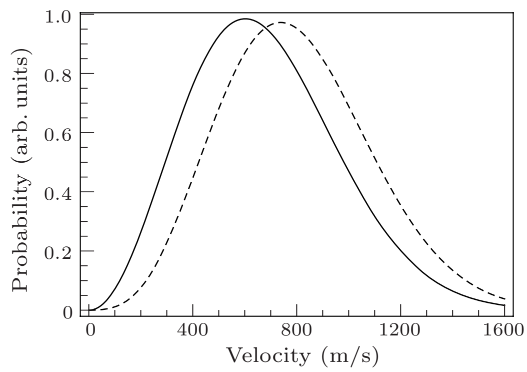

Fig. 3. Atomic velocity distribution curves in the calcium atomic beam, the solid line represents velocity distribution in the hot oven, the dashed line indicates velocity distribution in the thermal beam outside the oven. Here $m = 6.6\times10^{-26}\,\mathrm{kg}$, $T = 873\,\mathrm{K}$.

Comparing the left-side and the right-side in Fig. 2, for single-velocity atoms, we can use both the Rabi π pulse and adiabatic passage to obtain the atom excited to the upper level by modulating the laser power or laser waist. However, for a thermal atomic beam that has a wide velocity distribution, both procedures will not be successful. The π pulse always gives excitation of some of the atoms to the desired level but not all of them. However, for the adiabatic passage when the condition[13,17]

$$|\Delta\dot{\omega}(t)| \ll R^2(t=0) \quad (8)$$

is satisfied, almost all the atoms will be excited to the upper state.

The velocity distribution of the thermal atomic beam that be used in the calcium active optical clock obeys the Maxwell velocity distribution of a thermal beam:[16]

$$I(v)dv = \frac{2I_0}{\alpha^4}v^3\exp\Big(-\frac{v^2}{\alpha^2}\Big)dv, \quad (9)$$

where I_0 is the total flux and α is the most probable velocity $\alpha = \sqrt{2kT/m}$, as shown in Fig. 3. Then considering the velocity distribution of the atom beam from the oven, we will obtain the total probability that atoms be excited to the upper state.

As shown in Fig. 4, when the atomic beam crosses the laser beam right at the waist, Rabi oscillation is present under the curvature of the velocity distribution. However, at most 76% of the atoms will be excited to the upper level by adjusting the laser power and laser waist. When the atomic beam crosses the laser beam at a distance z from the laser waist and suitable laser parameters are selected to satisfy the condition Eq. (8), the adiabatic process will take place. As shown in Fig. 5, the total probability will increase as the distance z increases, and 99% of the atoms reside in the upper level after the interaction zone with suitable laser power and laser waist.

For a better qualitative understanding of the process of the adiabatic passage, this problem has been discussed within the framework of the dressed atom[13,14] and within the Bloch vector.[3,15]

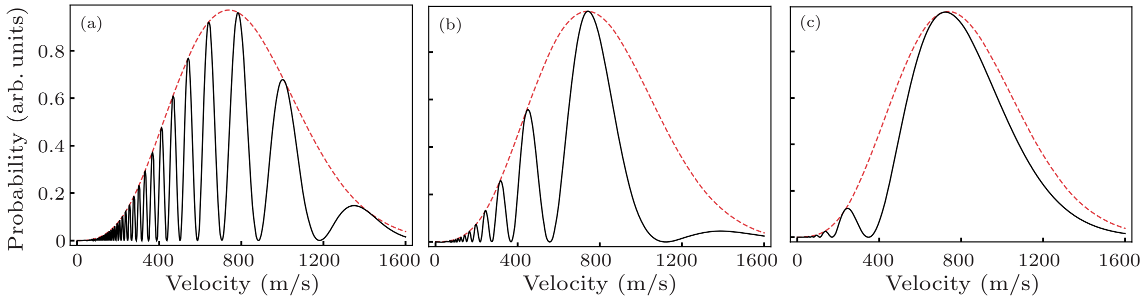

Fig. 4. Population inversion for the atomic beam after crossing the laser waist; the dashed line represents the velocity distribution, the solid line indicates the probability that corresponds to the velocity at which atoms are pumped to the upper level. The laser waist $w_0 = 1$ mm, the laser power is (a) $P = 40$ mW (b) $P = 4$ mW (c) $P = 0.4$ mW, the total probability is (a) 50% (b) 46% (c) 76%, respectively.

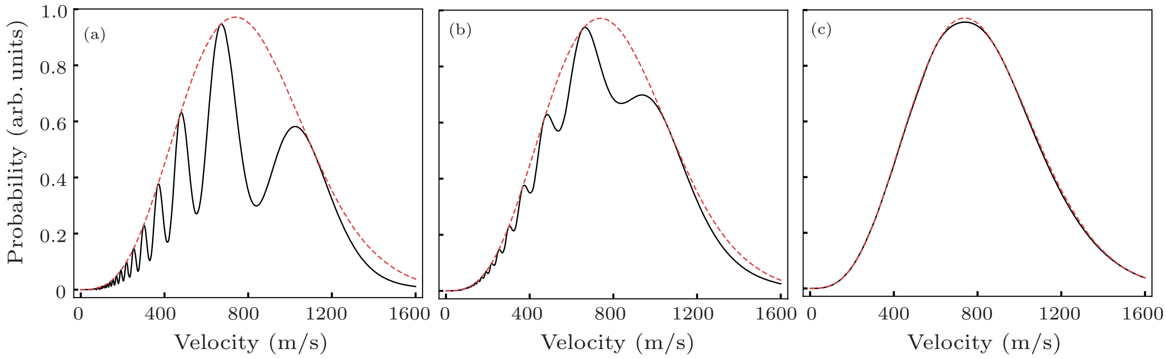

Fig. 5. Population inversion for the atomic beam crossing a distance z from the laser waist. The laser waist $w_0 = 0.2$ mm, the laser power is $P = 10$ mW, distance z: (a) $z = 0.1$ m, (b) $z = 0.2$ m, (c) $z = 0.5$ m. The total probabilities are (a) 67%, (b) 86%, (c) 99%, respectively.

In summary, we have proposed a new application of the adiabatic passage to produce the population inversion of a thermal atomic beam of calcium for an active optical clock. This scheme can also be used for other atomic beam excitation if the adiabatic condition is satisfied. However, we do not consider the linewidth of the laser in the calculation. In the experiment, the linewidth should be narrow enough such that the laser coherence time is longer than the transit time of an atom passing through the laser beam to realize the adiabatic passage.

References

[1] Shore B W et al 1992 *Phys. Rev.* A **45** 5297
[2] Abragam A 1961 *The Principle of Nuclear Magnetism*(Oxford: Clarendon)
[3] Treacy E B 1968 *Phys. Lett.* A **27** 421
Treacy E B and DeMaria A J 1969 *Phys. Lett.* A **29** 369
[4] Loy M T 1974 *Phys. Rev. Lett.* **32** 814
[5] Hulet R G and Kleppner D 1983 *Phys. Rev. Lett.* **51** 1430
[6] Gaubatz G et al 1990 *J. Chem. Phys.* **92** 5363
Shore B W, Bergmann K, and Oreg J 1992 *Z. Phys.* D **23** 33
[7] Broers B, van Linden van den heuvell H B and Noordan L D 1992 *Phys. Rev. Lett.* **69** 2062
[8] Goldner L S et al 1994 *Phys. Rev. Lett.* **72** 977
[9] Lawall J and Prentiss M 1994 *Phys. Rev. Lett.* **72** 993
[10] Esslinger T et 1986 *Phys. Rev. Lett.* **76** 3423
[11] Peik E et al 1997 *Phys. Rev.* A **55** 2989
[12] Chen J B 2009 *Chin. Sci. Bull.* **54** 348
[13] Kroon J P C et al 1985 *Phys. Rev.* A **31** 3724
[14] Ekstrom R and Kurtsiefer et al 1996 *Opt. Commun.* **123** 505
[15] Harold J.Metcalf and Peter van der Straten 1999 *Laser Cooling and Trapping* (New York: Springer) p 11
[16] Huang K K et al 2006 *Chin. Phys. Lett.* **23** 3201
[17] Wichman B, Liedenbaum C and Reuss J 1990 *Appl. Phys.* B **51** 358