Velocity-selective coherent population trapping in caesium ions

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Velocity-selective coherent population trapping in caesium atoms

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The extension to high angular momentum transitions of laser cooling below the recoil limit based on velocity-selective coherent population trapping (VSCPT) is explored. An efficient VSCPT can be realized only by applying a compensation of the kinetic energy mismatch between the components of the superposition wavefunction and introducing repumping on the hyperfine transitions. Theoretical and experimental progress for VSCPT on caesium atoms is discussed.

Laser cooling based on velocity-selective coherent population trapping (VSCPT) prepares atoms in a coherent superposition of ground states, i.e. an entangled state composed by internal variables and the external variables of the atomic momentum (see Aspect *et al.* 1988). The internal variables may correspond to the Zeeman components of a given angular momentum states, or to the Zeeman components of different hyperfine states. VSCPT has been successfully applied by Aspect *et al.* (1988) and Lawall *et al.* (1995) for operation on $1_g \rightarrow 1_e$ transitions in helium and by Esslinger *et al.* (1996) on rubidium. The $1_g \rightarrow 1_e$ transition has several important features. (i) The coherent superposition is made up by a limited number of ground state levels, two only in the case of VSCPT in one dimension; (ii) all the wavefunctions composing the entangled state have the same kinetic energy, so that a stationary coherent superposition is formed; and (iii) the atomic superposition wavefunction is isomorphic to the applied laser field. A limited progress has been made in the extension of VSCPT to high angular momentum transitions, where the $1_g \rightarrow 1_e$ features are not satisfied and where several additional conditions must be introduced for an efficient preparation. In the present work, the theoretical progress in the application of VSCPT to caesium atoms and in the experimental realization are discussed.

We consider atoms with mass M and excited state spontaneous decay rate Γ, interacting with a one-dimensional cooling laser field of wave number k, i.e. with recoil frequency $\omega_{\mathrm{R}} = \hbar k^2/2M$. The VSCPT laser field, composed by $\sigma^+ - \sigma^-$ counterpropagating fields, is characterized by the Rabi frequency Ω_{VSCPT} and detuning δ_{VSCPT}. For this VSCPT configuration, the $\Delta F = 0$ transitions have the advantage of producing only one coherent superposition non-coupled from the applied laser fields. For caesium atoms, excitation on the $3_g \rightarrow 3_e$ transition produces a non-coupled superposition with a smaller number of momentum components, i.e. the following one:

$$|NC(p)\rangle = (1/2\sqrt{7})[\sqrt{5}|3_{g,p,-3}\rangle + \sqrt{3}|3_{g,p,-1}\rangle + \sqrt{3}|3_{g,p,1}\rangle + \sqrt{5}|3_{g,p,3}\rangle], \tag{1.1}$$

where $|3_{g,p,m}\rangle$ describes a ground state with magnetic quantum number m and

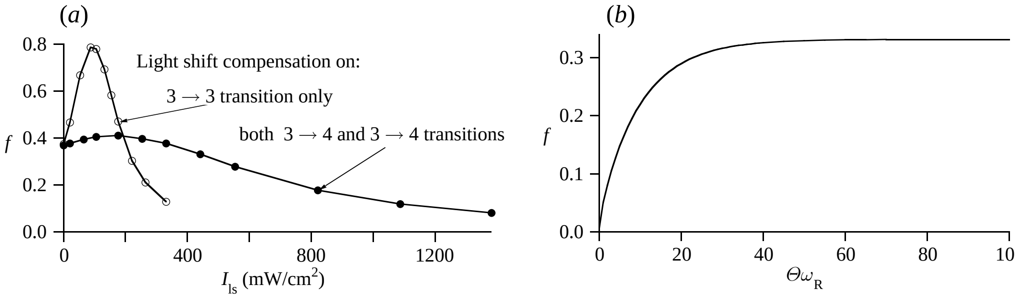

Figure 1. Results for the numerical analysis of caesium VSCPT on the $3_g \rightarrow 3_e$ transition. (*a*) Fraction of trapped population, f, at interaction time $\Theta = 100/\omega_R$ versus the light-shift laser intensity I_{ls} (in mW cm^{-2}) and other parameters $\Omega_{\text{VSCPT}} = 0.96\Gamma$, $\delta_{\text{VSCPT}} = 2.8\Gamma$, $\delta_{ls} = -630\Gamma$. The cases of light-shift laser exciting the $F_g = 3 \rightarrow F_e = 3$ transition only, or both the $F_g = 3 \rightarrow F_e = 3$ and $F_g = 3 \rightarrow F_e = 4$ transitions, are examined. (*b*) Trapped population versus the interaction time with light-shift laser exciting both hyperfine transitions, at $I_{ls} = 442$ mW cm^{-2} and other parameters as in (*a*).

momentum $p + m\hbar k$. The preparation of this superposition in a stable form requires to compensate for the difference in kinetic energy between the different momentum components. An additional π-polarized laser field near resonant with another $3_g \rightarrow 3_{e'}$ transition may produce a ground state compensated for that kinetic energy difference (see Foot *et al.* 1994). For the non-coupled wavefunction of equation (1.1), the light-shift energy $\hbar U_{ls}$ should satisfy the following relation:

$$U_{ls}(m = \pm 3) = 9U_{ls}(m = \pm 1). \tag{1.2}$$

Even if the light-shift laser is out of resonance, the non-coupled state experiences a small probability of absorption, γ_{ls}, which cannot be neglected in the long time evolution required for the VSCPT preparation. In the laser cooling of alkali atoms, the optical pumping towards an hyperfine ground state different from the one of atomic preparation requires the application of a repumping laser field. A repumping from the 4_g state should be applied also in the case of VSCPT in the 3_g state, for instance on the $4_g \rightarrow 4_e$ transition. For the results reported in figure 1*a*, $\sigma^+ - \sigma^-$ repumping configuration has been chosen. Our model takes into account the interaction between all the hyperfine levels composing the atomic optical transitions and the three lasers, for the VSCPT, the light-shift compensation and the repumping. By a proper choice of the parameters for the different laser fields, reported in the caption to figure 1*b*, it is possible to achieve a large filling rate of the non-coupled state.

The experimental realization of VSCPT on caesium atoms is based on a sequence of laser cooling operation. In a magneto optical trap excited by the $4_g \rightarrow 5_e$ transition of the D_2 line, 10^7–10^8 caesium atoms are trapped at temperatures in the 200 μK range. By switching off the applied magnetic field and applying a molasse phase, temperatures in the 4 μK range are reached for more than 5×10^6 atoms. In the final phase, the $\sigma^+ - \sigma^-$ VSCPT laser field acting on the $3_g \rightarrow 3_e$ D_2 transition, the π-polarized light-shift laser on the $3_g \rightarrow 3_e$ D_1 transition, and the repumping laser acting on the D_2 $4_g \rightarrow 4_e$ transition are applied. The VSCPT interaction time Θ is around $100/\omega_R$. After laser slicing of the atomic spatial distribution, the atomic momenta will be derived from the spatial distribution of the fluorescent light emitted by the atoms crossing an horizontal sheet of probe light located 10 cm below the interaction region. Temperatures in the 20–60 nK range are predicted from the theoretical analysis and roughly a total of 10^3 atoms will be needed to resolve the VSCPT momentum distribution.

Using the outcome from the atomic preparation into VSCPT states with high angular momentum, the h/m constant may be determined from a measurement of the recoil frequency ω_{R}. If, after a preparation phase, the VSCPT and light-shift compensating lasers are eliminated, the free-flight time evolution between coupled and non-coupled states contains a beat frequency at a multiple of the recoil frequency. That frequency may be extracted from the absorption measurement for a VSCPT field applied at the end of the free-flight evolution. By using an initial narrow momentum distribution, with width around $\hbar k/100$, and a free-flight time around $100/\omega_{\mathrm{R}}$, the fraction of the recoil time is small enough to reach an accuracy in h/m of 1×10^{-7} part. A large increase in the accuracy of the determination could be obtained if this free-flight evolution is included within the evolution of an atomic interferometer, in analogy to the atomic interferometer based on dark states used by Weitz *et al.* (1996).

In conclusion, the preparation of atomic states into superposition of high angular momentum states could be important for the creation of high-order coherences, for the preparation of atoms into states useful for atomic interferometry and for the new determination of fundamental constants.

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