Optics Communications 324 (2014) 258–263

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Continuous loading of an atom beam into an optical lattice

Vladyslav V. Ivanov

24 Princeton street, North Chelmsford, MA 01863, USA

ARTICLE INFO

Article history:
Received 10 November 2013
Received in revised form
2 February 2014
Accepted 16 March 2014
Available online 27 March 2014

Keywords:
Sisyphus cooling
Cold atoms
Continuous atom laser

ABSTRACT

I propose a method of deceleration and continuous loading of an atom beam into a far-off-resonance optical lattice. The loading of moving atoms into a conservative far-off-resonance potential requires the removal of the atom's excess kinetic energy. Here this is achieved by the Sisyphus cooling method, where a differential lattice-induced ac Stark shift is utilized. The proposed method is described for the case of ytterbium atoms. Numerical simulations demonstrate the possibility of reaching cold and dense samples in a continuous manner on the example of ytterbium atoms.

1. Introduction

Matter-wave interferometry with ultra-cold atoms holds great promises for precision measurements. Pioneering experiments have demonstrated the possibilities of the measurements of photon recoil and Earth's gravity acceleration [1–4]. More recently, very accurate measurements of the fine structure constant have been performed in the group of Biraben [5]. Atom interferometry was used for measurements of the gravitational constant [6,7], the least accurately known fundamental constant. Although matter-wave interferometry greatly benefits from short de Broglie wavelength of laser cooled atoms, it is still far behind in terms of flux, i.e. the number of available particles per time-interval, when compared to more common optical interferometers. Obtaining a bright source of ultra-cold atoms can be crucial for further advances in matter-wave interferometry.

Traditionally, atoms used in matter-wave interferometry experiments are, first, loaded into magneto optical traps (MOTs), followed by an intermediate polarization gradient cooling stage or a compressed MOT stage. Then these atoms are either immediately used for measurements [2,5,6] or loaded into conservative traps for further manipulation [3,4]. However, such methods imply a time sequence of cooling steps, which restricts the loading rate of atoms. Continuous production of ultra-cold atoms can increase the available atomic flux for matter-wave interferometry experiments. Furthermore, it can potentially offer the possibility of preparing Bose–Einstein condensates (BECs) continuously with a substantially increased flux. A spectacular application of this would be the realization of an atom laser, the matter wave analogue to an optical cw laser. A continuous atom laser would provide an extremely bright and coherent source of matter that promises significant improvements of precision measurements and might open novel ways for fundamental tests of quantum mechanics [8].

In this paper I propose the method of a dissipative deceleration and continuous loading of an atomic beam into a standing wave potential of optical lattices. The method includes a Sisyphus cooling mechanism which allows the removal of excessive kinetic energy. The proposed method exploits the differential ac Stark shift induced by the optical lattice potential, similar to [9]. Atoms are pumped into the excited state using an additional pumping beam that is tuned near a resonance at the node of the lattice potential. In the excited state, atoms dissipate their kinetic energy by climbing the "hills" of the lattice potential. Eventually, atoms decay into the ground state and this cycle repeats until the atoms have spent all their energy and are trapped in anti-nodes of the optical lattice. Atoms trapped in the conservative optical lattice potential are essentially sitting in the "darkness" due the large ac Stark shift. The presented Sisyphus cooling mechanism is different from other Sisyphus cooling schemes demonstrated previously [10–15] in two regards: (1) Atoms do not need to be pre-cooled or trapped, (2) Atoms cooled below a certain energy do not scatter cooling photons and thus they are essentially decoupled from the cooling cycle. The described scheme can be modified by introducing a small frequency difference for the optical lattice beams, creating an "atomic conveyor belt" [16,17], which allows continuous production of cold and dense atom samples.

The proposal is described for the case of ytterbium atoms, although an application of the proposed method on other atomic species is possible. Ultra-cold samples of Yb atoms are of great interest in the context of precision measurements including optical clocks [18] and matter-wave interferometry [19,20].

E-mail address: vladivanov78@gmail.com

http://dx.doi.org/10.1016/j.optcom.2014.03.042
0030-4018/

The method, I describe, is similar to the scheme proposed by Aghajani-Talesh et al. [21], where the dissipation of atom energy is achieved by pumping atoms into different magnetic states at the top of the magnetic barrier. However, the scheme was proven to be effective in a recent experiment for loading atoms into an optical dipole trap (ODT) [22]. This scheme is limited to atomic species with magnetic sub-levels in the ground state. Moreover, although an injection of an atomic beam into an ODT was demonstrated, uncoupling of the atoms cooled in the ODT in a continuous way still has not been proposed.

The rest of this paper is organized as follows. In Section 2, I discuss the general requirements for the proposed loading method. I perform a simple calculation for the efficiency of the loading process and discuss its limitations. In Section 3 I develop a numerical model that addresses the stochastic nature of the process and computes expected atom dynamics. In Section 4, I discuss reachable loading rates and density of atomic samples in an experiment with realistic parameters. I draw my concluding remarks in Section 5.

2. The deceleration scheme

The basic idea of the deceleration scheme is shown in Fig. 1. An atomic beam is moving towards a trapping region where the optical lattice beams and pumping beams intersect. The pumping beams are tuned near the resonance for the atoms at the nodes of the optical lattice and is perpendicular to the atomic beam. In the transverse direction the pumping beams assumed to have diameters substantially larger than the optical lattice, the diameters of pumping beams in the longitudinal direction essentially define the deceleration region. The optical lattice is aligned along the atom beam or crosses it at a very shallow angle. The optical lattice potential, which is attractive for the atom in the ground state but repulsive in the excited state, is playing a double role: (1) it provides potential hills on which atoms spend their energy and (2) it provides trapping potential for atoms that have already dissipated their kinetic energy. When an atom scatters one pumping photon, it leads to a loss of atomic energy roughly equal to lattice trap depth. This energy loss can be much larger compared to the energy loss during Doppler cooling, which is proportional to a photon recoil momentum. After the atom energy drops below the lattice trap depth, the atom is trapped in a lattice site and does not

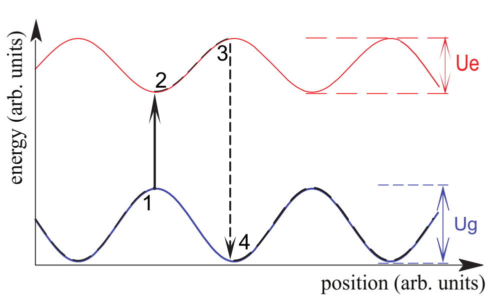

Fig. 1. Continuous loading scheme for a two-state cooled species in optical lattices. An additional pumping beam, resonant with the transition, is also directed at the trapping region. The solid upper red (lower blue) curve shows the spatially varying lattice potential, where $U_e(U_g)$ is the lattice potential amplitude for the excited (ground) state. The pumping laser is tuned near the resonance for an atom at the zero of the trapping potential, i.e. nodes of the optical lattice. The cooling proceeds via the following cycle: (1) a moving atom absorbs a photon at a node of the lattice potential; (2) it climbs a repulsive potential (upper red curve); (3) it spontaneously decays into the ground state (lower blue curve); (4) as the atom continues to move in the lattice potential, it absorbs another photon near the node of the lattice and the cycle repeats. Trajectory of the atom is shown as a dashed black curve. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

scatter any more cooling photons due to the ac Stark shift. The proposed method critically relies on the spatially selective pumping of atoms into the excited state, which is achieved using the ac Stark shift provided by the optical lattice potential.

An important requirement of this method is that the ac Stark shift of the excited state should be larger than the ground, i.e. the optical lattice for the atoms in the excited state has to be either repulsive or if it is attractive it must have smaller ac Stark shift than for the ground state. The linewidth of the pumping transition is another crucial parameter. Relatively narrow transitions with a linewidth below 1 MHz are preferable because they allow pumping of the atoms precisely at the nodes of an optical lattice. As it is shown below, another advantage of a narrow transition is a longer decay time into the ground state, which makes the deceleration method efficient for lower velocities (see Eq. (4)). However, broad transitions can provide high scattering rate, which would increase probability of pumping into the excited state, and thus increase capturing velocity (Eq. (3)). The linewidth of the pumping transition is a trade-off between higher capture velocity and ability to decelerate atoms to lower velocities. For realistic experimental parameters the described method will work efficiently for pumping transition in the range between $2\pi \times 10$ kHz and $2\pi \times 1$ MHz.

To estimate a maximum capturing velocity and number of scattered photons I first consider the 1D case. Let us assume that photon absorption occurs strictly at the nodes of the optical lattice. If the atom velocity is high, the atom can propagate through the lattice potential for distances substantially larger than the lattice period during the typical time scale of spontaneous decay into the ground state. In this case the position of where the atom decays into the ground state is not correlated with the position of the lattice potential minima or maxima. In this approximation the atom loses the average energy $U_d = (U_e\, U_g)/2$ per cycle. In order to decelerate an atom with the initial kinetic energy E_0, the atom should scatter $\sim E_0/U_d$ photons. For a deceleration region with size l_d, the number of trapping lattice sites N_s is about $2l/\lambda$, where the λ is the lattice wavelength. In the deep lattice approximation the probability to absorb a cooling photon can be estimated as

$$p = \frac{\gamma\lambda}{2v_0}\sqrt{\frac{\hbar\gamma}{U_d}}, \qquad (1)$$

where v_0 is the atom velocity and γ is the linewidth of the transition. The atom moving through the cooling region will dissipate the energy $E_d = p \times N_s \times U_d$, on the order of

$$E_d \simeq \frac{\gamma\lambda}{2v_0}\sqrt{\frac{\hbar\gamma}{U_d}\frac{2l_d}{\lambda}}U_d. \qquad (2)$$

After atom energy drops below U_g, the atom stops propagation and is trapped in the lattice potential. The initial kinetic energy dissipated in such a system is

$$v_0^6 \simeq 4\gamma^2 l_d^2 \times \hbar\gamma \times U_d/m^2. \qquad (3)$$

The maximum capture velocity does not depend on the lattice wavelength. It is worth noting that this result is valid only the deep optical lattice, i.e. $\hbar\Gamma\, U_d$. For the case of ^{174}Yb, $U_d = 1$ mK, and l_d=5 cm, $v_0 \simeq 8$ m/s, atoms with this initial velocity or lower will be decelerated and trapped. This velocity is comparable to the capture velocity reached in conventional Yb MOT [23]. The described method becomes less efficient for lower velocities. When the assumption that atoms in the excited state propagate through the lattice potential for distances substantially larger than the lattice period fails, the dissipative process becomes inefficient. The expected energy ε the atoms lose after scattering a photon at the node of the lattice potential is (assuming that change of atom's