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Bright, slow, and continuous beam of laser-cooled cesium atoms

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By the moving molasses technique we have extracted laser-cooled cesium atoms in a continuous way directly from an optical molasses. The mean launching velocity is precisely tunable from 1 to 12 m/s. The atomic beam has a flux of 1.3×10^8 atom/s at 7 m/s and a longitudinal temperature of 70 μK, which represents the highest flux and lowest velocity spread obtained so far in a continuous beam of cold atoms. These features makes it well suited for atomic fountains. The atomic flux can be slightly increased in a two-dimensional magneto-optical trap operation (+40%). A simple model accounts for the observed dependence of the flux with the magnetic-field gradient. [S1050-2947(99)51212-2]

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I. INTRODUCTION

The technique of laser cooling of atoms has stimulated several developments in the production of slow and bright atomic beams for many applications in atomic spectroscopy, collision studies, atom optics, atomic interferometry, and atomic frequency standards. The first demonstrations of cold beams were achieved by slowing thermal beams by frequency-chirped lasers [1] or by Zeeman tuning [2]. In order to increase the atomic density, the slowed beam was compressed by a two-dimensional (2D) magnetic field gradient [3,4]. Various techniques have been used to extract atoms continuously from magneto-optical traps (MOTs) loaded in a vapor cell. By a controlled unbalanced light pressure in continuous operation [5] or in a pulsed mode [6], atomic fluxes up to 5×10^9 atom/s were measured, but with comparatively high mean velocity (7–20 m/s) and velocity spread [2–3 m/s full width at half maximum (FWHM)]. Continuous beams of cold atoms were produced from a 2D MOT with a magneto-optical extraction [7,8]. The atomic flux (1.3×10^8 atom/s) was smaller than in [5], but the launching velocity was lower (0.7–3 m/s), and the typical velocity spread was as small as 0.26 m/s FWHM [8]. The moving molasses technique is also suitable for extracting cold atoms continuously, as first demonstrated on a small flux (10^6 atom/s) in [7].

In the present work we load a cold atomic cesium trap directly from a vapor cell, and we extract continuously cold atoms with the moving molasses technique. We report experimental results on atomic beams produced either from a 2D MOT, or simply from an optical molasses (3D OM), in which case the magnetic-field gradient is switched off. The flux intensity is 1.3×10^8 atom/s in a 3D OM operation, and only slightly increased in a 2D MOT operation (+40%). Moreover, that no-magnetic-field environment leads to much lower beam temperature (70 μK or 0.15 m/s FWHM velocity spread) and allows a more precisely tunable launching velocity than in [4] (1–12 m/s, both adjustable and proportional to the moving molasses frequency detuning to better than 0.02 m/s).

To understand the dynamical behavior of extracted atoms in the 2D MOT, we have developed a simple 2D model of the extraction process, taking into account the transverse magneto-optical force. The model predicts that the atomic beam can be focused, an effect that is consistent with our observations.

II. EXPERIMENTAL SETUP

Cesium atoms are cooled in a $\sigma^+-\sigma^-$ 3D OM loaded from a thermal vapor (10^{-8} mbar). Our beam geometry uses four independent cooling beams in the Oyz plane at $\alpha=\pm45°$ with respect to the vertical direction and one retroreflected beam parallel to the Ox axis (Fig. 1). Each cooling beam (red-detuned from the $F=4\rightarrow F'=5$ hyperfine transition of the Cs D_2 line, $\lambda=852.1$ nm) is Gaussian

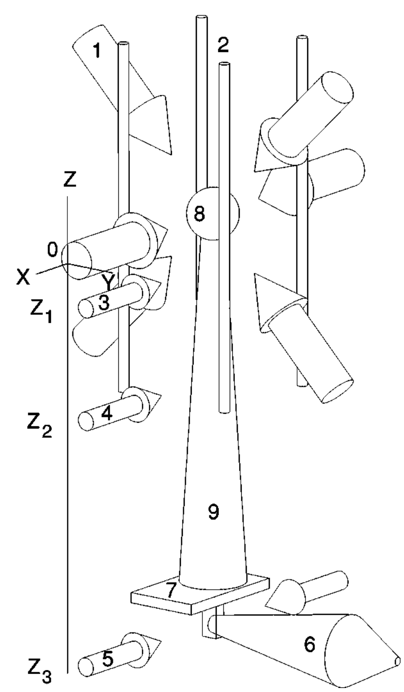

FIG. 1. Experimental setup: 1, cooling beams [downgoing (upgoing) beams are frequency shifted by $|\Delta\nu|$ $(-|\Delta\nu|)$ with respect to Ox beams]; 2, 2D magnetic gradient wires; 3, optical pumping beam ($z_1=-20$ mm); 4, pushing beam ($z_2=-86$ mm); 5, probe beams ($z_3=-393$ mm); 6, atomic fluorescence light; 7, removable diaphragm (5×3 mm^2); 8, cold atomic source; 9, cold atomic beam.

shaped and has a power of up to 20 mW and a diameter at e^{-2} of 25 mm. An additional repumping beam ($3\rightarrow 4'$ transition) is added to the Ox beams. This geometry leaves the vertical direction in which an atomic beam is produced (see Sec. III) free of any superimposed laser beam. This 3D OM configuration can be transformed into a 2D MOT configuration by applying an additional magnetic-field gradient produced by opposing currents in four vertical copper wires. The effect of this gradient is discussed in Sec. IV. Three sets of Helmholtz coils provide the required compensation for the earth's magnetic field.

Most atoms leaving the 3D OM or the 2D MOT are in the $F=4$ state, but, due to optical pumping by the fluorescence light of the trap, the population of the $F=3$ state increases during the fall. A total population inversion can be forced at the exit of the trap by preparing all extracted atoms in the dark $F=3$ state with a depumping beam ($4\rightarrow 4'$ transition). Below we have implemented a pushing laser beam ($4\rightarrow 5'$ transition) mixed with a repumping beam ($3\rightarrow 4'$ transition) for diagnostic purposes. Finally we detect the cold atoms by fluorescence in a retroreflected probe laser beam ($4\rightarrow 5'$ transition) just below a removable diaphragm. The pushing and probe beams can be used in a time-of-flight (TOF) measurement mode, allowing velocity and longitudinal temperature measurements.

III. CONTINUOUS BEAM FROM A 3D OM

In order to extract cold atoms continuously either from the 3D OM or from the 2D MOT, we use the moving molasses technique. By shifting the frequency of the downgoing (upgoing) -laser beams by an amount $|\Delta\nu|$ $(-|\Delta\nu|)$ with respect to the frequency of the Ox beams, atoms are cooled in a reference frame moving downwards. The atomic mean launching velocity is $\overline{v_l}=(\lambda/\cos\alpha)\Delta\nu$ where $\lambda/\cos\alpha=1.205$ μm is the relevant wavelength of the interference pattern in the vertical direction [7].

The mean launching velocity $\overline{v_l}$ can be calculated from the measured TOF signal of a slice of the atomic beam released by a short interruption (1 ms) of the pushing beam. Considering gravity only, the mean launching velocity $\overline{v_l}$ plotted against the moving molasses frequency detuning $\Delta\nu$ yields an affine regression [$\overline{v_l}$ (m/s)$=0.19+1.185\Delta\nu$ (MHz)]. The calculated velocity offset at $\Delta\nu=0$ cannot be accounted for by either uncertainties in the geometrical setup (beam heights and alignments), in the timing, or in the residual magnetic field. However, we have noticed that the TOF distributions are increasingly affected (center and width) as the fluorescence light from the trap is allowed to become stronger. We have measured this fluorescence light intensity and we have recalculated the atomic motion for each $\Delta\nu$ value including the corresponding light pressure force. The corrected linear regression (Fig. 2) totally agrees with the theoretical prediction [$\overline{v_l}$ (m/s)$=0.003+1.206\Delta\nu$ (MHz)].

The longitudinal temperature T_l of the atomic beam is inferred from the TOF distribution width. In Fig. 2 we notice that it is about 70 μK for launching velocities between 2 and 6 m/s. Outside this range, TOF signals are very weak and somewhat asymmetric, leading to inaccurate temperature

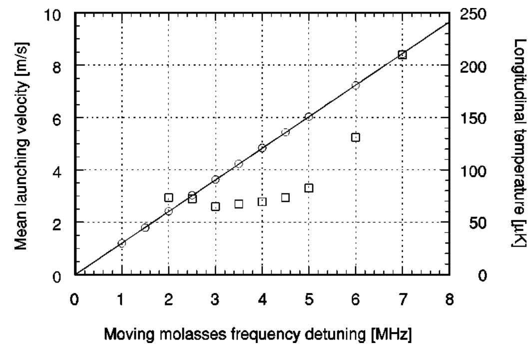

FIG. 2. Mean launching velocity $\overline{v_l}$ (○) and longitudinal temperature T_l (□) of the atomic beam vs moving molasses frequency detuning $\Delta\nu$. The beam is extracted from the optical molasses. The linear fit totally agrees with the theoretical prediction [$\overline{v_l}$ (m/s) $=0.003+1.206\Delta\nu$ (MHz)]. Errors bars for $\overline{v_l}$ are smaller than the open circles' diameter.

estimates. For $\overline{v_l}\geqslant 6$ m/s the time spent by an atom in the moving molasses (5 ms) becomes comparable with the Doppler cooling time and not all atoms reach the sub-Doppler cooling capture velocity. Therefore the longitudinal temperature is expected to increase with initial velocity, a trend that is indeed observed.

As we investigate the continuous beam in a range of small initial velocities ($\overline{v_l}\leqslant 6$ m/s), the parameters optimizing the beam flux are close to those maximizing the capture rate of the trap (18 mW per laser-cooling beam, global frequency detuning $\delta=-2.5\Gamma$, where $\Gamma=2\pi\times 5.3$ MHz is the natural width of the cooling transition). We estimate the atomic beam flux by measuring the signal-to-noise ratio (S/N) of the fluorescence light in the probe region. This method has the advantage of being totally independent of the calibration of the fluorescence detection efficiency, provided that more than one photoelectron is generated in the photodetector for each atom of the beam. Since this condition is fulfilled in our detection setup, the atomic flux detected is $\Phi=2(S/N)^2$, where S is the photocurrent dc value and N is the white-noise spectral density due to the atomic shot noise [9]. In Fig. 3 we have plotted against $\overline{v_l}$ the atomic flux Φ extracted from the 3D OM and detected at the probe level. It reaches $\Phi=1.3\times 10^8$ atom/s at $\overline{v_l}=7$ m/s. For $\overline{v_l}\geqslant 0.2$ m/s the atomic loss rate of the trap is dominated by the extraction into the continuous beam, and therefore the total flux is limited by the capture rate of the trap. The beam divergence angle becomes smaller as $\overline{v_l}$ increases, so the detected fraction of the total flux becomes greater and approaches the capture rate. However, as mentioned above, for $\overline{v_l}\geqslant 6$ m/s the capture rate decreases due to uncompleted Doppler and sub-Doppler cooling processes, which results in the observed flux reduction. For $\overline{v_l}=3.6$ m/s (typical launching velocity for an atomic fountain) the flux density through the calibrated diaphragm (5×3 mm^2) is 2×10^8 atom/s cm^{-2}, 90 ms away from the trap, which corresponds to a tenfold increase over the results obtained with the magneto-optical extraction [8]. In comparison with [7], where a cold continuous beam is also produced by the moving molasses technique but from a 2D MOT, our atomic flux

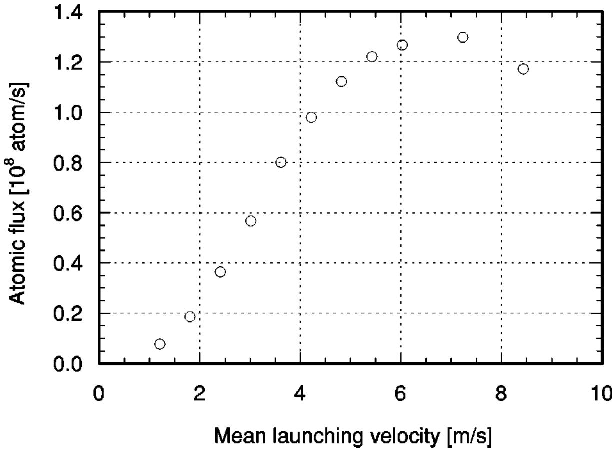

FIG. 3. Atomic flux Φ vs mean launching velocity $\overline{v_l}$. The beam is extracted from the optical molasses at optimal laser cooling power (18 mW per beam) and global frequency detuning ($\delta = -2.5\Gamma$).

is greater by two orders of magnitude in the same velocity range. The main differences between the two experiments are the beam geometry (45° instead of 14°), a bigger beam diameter, and a better beam homogeneity (optical fibers).

IV. ATOMIC FLUX FROM A 2D MOT

We have measured the atomic flux Φ as a function of the 2D magnetic gradient b (Fig. 4). For $\overline{v_l} = 3.6$ m/s, the flux is maximum at $b = 5$ mT/m, and drops very sharply above. The flux is even five times smaller at $b = 125$ mT/m than at $b = 0$ mT/m, which is counterintuitive, since the transverse magnetic gradient is expected to reduce the atomic beam diameter at the level of the source, and consequently to increase the detected flux. In order to explain this unexpected behavior we have developed the following two-dimensional Monte Carlo simulation of atomic trajectories inside and outside the trap.

An atom entering the MOT is subjected to the well-known transverse magneto-optical force $F = -\alpha v - \kappa x$ where the damping and restoring coefficients α and κ are calculated analytically in the induced-orientation theory for a $J = 1 \rightarrow J' = 2$ transition in one dimension [10]. For the typical operational parameters of our experiment, calculated values are $\alpha = 3.4 \times 10^{-21}$ kg/s and $\kappa = 10^{-20}$ kg/s^2 (mT/m)$^{-1}$ for a global frequency detuning $\delta = -2.5\Gamma$. In the trap, the longitudinal velocity is assumed to be equal to that of the moving molasses; the initial transverse position and velocity as well as the height of the atom entering the trap are random parameters in the range of the laser beam diameter and capture velocity. The equation of motion of the atom in the trap is solved numerically, yielding transverse position and velocity at the exit of the trap. As $b \leqslant 125$ mT/m the atomic trajectories are always overdamped, but the time spent in the cooling beams is not sufficient for atoms to reach their equilibrium position. At this stage a random transverse velocity in the range of the measured longitudinal temperature T_l is added to take into account a transverse temperature of the beam. Then the atomic trajectories outside the trap are deduced from ballistic laws with the calculated initial conditions. It is to be noted that the magnetic deflection due to the field gradient below the trap is negligible. The computed atomic beam flux is proportional to the number of atoms crossing the probe laser beam, where we take into account the finite dimensions of the detection area.

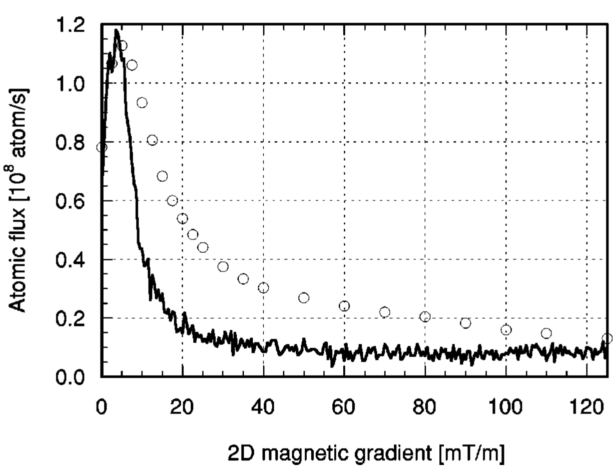

FIG. 4. Atomic flux Φ vs 2D magnetic gradient b. Open circles (○) are experimental data and the noisy full curve is a Monte Carlo simulation of atomic trajectories including the magneto-optical force in the trap and gravitation. The mean launching velocity is $\overline{v_l} = 3.6$ m/s.

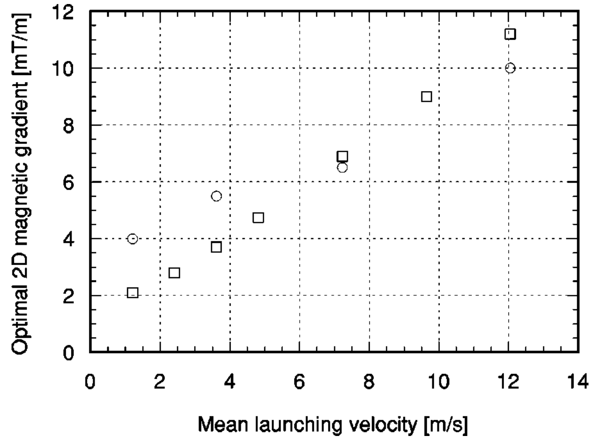

FIG. 5. Optimal 2D magnetic gradient b_{opt} maximizing the atomic flux Φ for different mean launching velocities $\overline{v_l}$. Open circles (○) are experimental data and open squares (□) are Monte Carlo simulation data.

In Fig. 4 we note the good agreement of our simple model with the experimental data. We have assumed a constant transverse temperature of 100 μK, which is the mean longitudinal temperature of the beam in our range of magnetic gradient. The beam flux ratio between 0 and 5 mT/m depends on the transverse temperature. With 100 μK, our model predicts a 60% flux increase, which slightly overestimates the experimental value (40%). We interpret the behavior of the atomic flux with the 2D magnetic gradient as a focusing effect of the atomic beam, which has been observed with numerical simulation. For $b = 5$ mT/m and $\overline{v_l} = 3.6$ m/s, the atomic beam ''waist'' is located at the probe level. For weaker magnetic gradient the atomic trajectory angles are smaller, which corresponds to a more distant focus point, and also to a smaller detected beam flux. On the other hand, at higher magnetic gradient the atomic beam ''waist'' moves closer to the source, which also reduces the atomic flux measured at the probe level.

In order to confirm our model we have repeated the previous measurement for different launching velocities $\overline{v_l}$. In Fig. 5, we have plotted the magnetic gradient b_{opt}—which corresponds to the maximum flux value—against $\overline{v_l}$. Both simulated and experimental data show a steady increase of b_{opt} with $\overline{v_l}$, which is understandable again with the beam focusing effect. As the TOF decreases with $\overline{v_l}$, the magnetic gradient must be increased to always focus the atomic beam at the probe level.

V. CONCLUSION

We have demonstrated that the moving molasses technique is very efficient for producing a continuous beam of laser-cooled cesium atoms. The atomic beam has a flux of up to 1.3×10^8 atom/s in a 3D OM operation, a longitudinal temperature of 70 μK (0.15 m/s FWHM velocity spread), and a launching velocity precisely tunable from 1 to 12 m/s. In contrast to the continuous beam described in [5], the 45° beam geometry leaves the atomic beam free of any superimposed laser beam, whose undesirable effects are thus strongly reduced (light shifts of energy levels, beam acceleration, and heating). All the above characteristics make the present setup particularly suitable for high-precision measurements (atomic interferometry, atomic spectroscopy, collision studies, and frequency standards). In particular, the low velocity range and the low longitudinal temperature are well suited to the atomic fountain [11].

The atomic flux can be slightly increased in a 2D MOT operation (40%). A simple 2D simulation of atomic trajectories inside and outside the trap supports experimental observations that the atomic beam can be focused by adjusting the magnetic gradient intensity and the launching velocity.

Further improvements of the continuous beam technique are possible: preliminary measurements show that additional transverse cooling at the exit of the trap is a promising technique to further reduce the beam divergence (especially for the 3D OM) and thus increase the atomic flux density after a long travel time (atomic fountain [11]).

ACKNOWLEDGMENTS

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