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A Source of Cold Atoms for a Continuously Loaded Magnetic Guide

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Abstract

We present an intense source of ^{87}Rb atoms that has been set up to produce a continuous, slow and cold beam in a magnetic guide. It consists of a two-dimensional magneto-optical trap whose cooling laser power is provided by a master-oscillator tapered-amplifier system. This trap produces an atomic beam with a flux of over 10^{10} atoms/s and a mean velocity of 40 m/s. The beam is recaptured by a second trap whose purpose consists in reducing the beam's velocity, in further cooling the atoms and injecting them into the magnetic guide. The article focusses on the first stage of the process described above.

1. Introduction

A spectacular challenge in the field of Bose–Einstein condensation consists in the achievement of a continuous beam operating in the quantum degenerate regime. This would be the matter wave equivalent of a cw monochromatic laser and it would allow for unprecedented performances in terms of focalization or collimation. In Ref. [1], a continuous source of Bose–Einstein condensed atoms was obtained by periodically replenishing a condensate held in an optical dipole trap with new condensates. This kind of technique raises the possibility of realizing a continuous atom laser. An alternative way to achieve this goal has been studied theoretically in Ref. [2]. A non-degenerate, but already slow and cold beam of particles, is injected into a magnetic guide [3–10] where transverse evaporation takes place. If the elastic collision rate is large enough, efficient evaporative cooling can lead to quantum degeneracy at the exit of the guide. The condition for reaching degeneracy with this scheme can be formulated by means of three parameters: the length ℓ of the magnetic guide on which evaporative cooling is performed, the collision rate γ at the beginning of the evaporation stage, and the mean velocity v_b of the beam of atoms. Following the analysis given in Ref. [2], one obtains

$$\frac{\gamma\ell}{v_b} \gtrsim 500. \tag{1}$$

Physically, (1) means that each atom has to undergo at least 500 elastic collisions during its propagation through the magnetic guide.

Our experiment aims at implementing this scheme for a beam of ^{87}Rb atoms. Its success relies therefore upon two preliminary and separate accomplishments. First, one has to build an intense source of cold atoms, with the lowest possible mean velocity. Second, one has to inject the atomic beam produced by this source into a long magnetic guide with minimal transverse and longitudinal heating. In our experiment, we subdivide the first task into the production of an intense atomic beam which is only subsequently further slowed down and cooled.

We generate a high flux of atoms by means of a two-dimensional magneto-optical trap (2D-MOT). Atoms of the beam produced by this source are recaptured by a second atom trap whose purpose consists in injecting the atoms into the magnetic guide with a very low velocity ($v_b \simeq 1$ m/s) that can be chosen at will. The present paper characterizes our 2D-MOT and is organized as follows: the principle of operation of the experiment is presented in section one. The second and third part of the paper respectively describe the experimental setup and the results that we have obtained so far.

2. Principle of operation

In order to inject atoms into the magnetic guide, we use a magneto-optical trap (MOT) based upon four laser beams in a tetrahedral configuration superimposed with a magnetic two-dimensional quadrupole field. The setup consists of a moving molasses [20] in the longitudinal direction combined with cooling and confining forces in the transverse directions and will be called *injecting MOT* in the following. A detailed description can be found in Ref. [21]. The injecting MOT allows to capture atoms entering the trapping volume with a velocity $v < v^*$, where v^* is a function of the available laser power, and to subsequently slow the atoms down to the final velocity v_b which only depends on the relative frequencies of the laser beams. In this way we produce an atomic beam with a temperature on the order of 50 μK and a velocity in the range of 30 cm/s to 3 m/s.

If the injecting MOT is loaded from a rubidium background gas with vapor pressure p, it captures atoms at a rate proportional to p. However, collisions between captured and thermal background atoms will limit the flux Φ of outgoing atoms to

$$\Phi \propto p \exp\left(-\frac{\alpha p}{v_b}\right), \tag{2}$$

where α depends on the characteristic length of the trap and the collision cross section. This process sets an upper limit $\Phi_{max} = \max_{\{p\}}(\Phi)$ to the flux that can be achieved. It decreases as $\Phi_{max} \propto v_b$ with decreasing velocity v_b. Since $\gamma \propto \Phi/v_b$, it also limits the collision rate in the magnetic

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guide provided that the temperature and the confining force of the guide are unchanged. In our previous setup in Ref. [21], we were able to produce a flux of 10^9 atoms/s at $v_b = 2.5$ m/s and a pressure $p = 4 \times 10^{-8}$ mbar. In order to overcome this limitation, we have to operate the injecting MOT in an ultra-high vacuum chamber.

For this purpose, many techniques have been developed. Thermal beams can be slowed down by means of a Zeeman slower in Ref. [13]. Alternatively, a collimated beam of atoms can be obtained by a vapor-loaded MOT with a leak at its center. For instance, one can drill a hole in one of the mirrors of a MOT [14,11]), or use a pyramidal mirror structure with a hole at its vertex [15–17], or use an extra pushing beam, which destabilizes the MOT at its center [18,19]. A third method for producing a cold beam of atoms relies on a 2D-MOT [11,12]. All these sources produce a relatively intense beam (from 10^6 to several 10^{10} atoms/s), with an average velocity $\bar{v}$ between 10 and 50 m/s. In our setup, we have implemented the 2D-MOT scheme. We note that the relation (2) also applies to the source producing the atomic beam. However, it is much less restrictive since the atomic velocities at its exit are orders of magnitude higher than in the injecting MOT.

3. Experimental setup

A schematic drawing of the experimental setup is shown in Fig. 1. The first MOT is located in a rectangular quartz cell (80 mm × 45 mm × 45 mm) connected to a Rubidium reservoir by a valve (not shown in Fig. 1) and joined to the main part of the vacuum system by a differential pumping tube. It is a vapor-loaded two-dimensional MOT based on a design that has been characterized in detail in Refs. [11,12]. For a thermal atom to be captured by the MOT, firstly it needs to have a transverse velocity smaller than the MOT's capture velocity. Secondly, the atom's longitudinal velocity $v_\parallel$ has to be low enough so that the transit time $\tau = l/v_\parallel$ (l being the length of the MOT) is sufficiently long for the atom to be transversally trapped and cooled. In this way the 2D-MOT produces two beams of atoms which leave the trap on axis in opposite directions.

Two pairs of elongated coils in anti-Helmholtz configuration produce a two-dimensional quadrupole magnetic field whose zero-field line is parallel to the optical table and centered with respect to the glass cell. Typical field gradients are on the order of 12 G/cm. The cooling laser light for the MOT is produced by a tapered amplifier providing up to 450 mW of light. The amplifier is injected

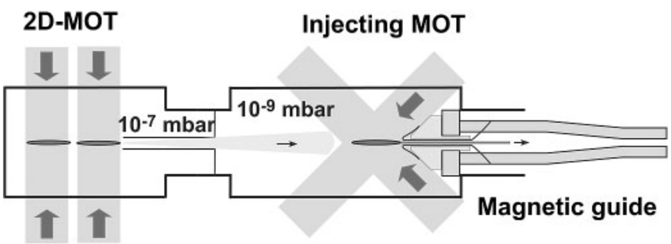

Fig. 1. Schematic drawing of the experimental setup. Atoms are captured from the background gas by the 2D-MOT which creates an atomic beam that is (partly) recaptured by the injecting MOT. The latter injects atoms into the magnetic guide with well-controlled velocity.

by a grating-stabilized diode laser which is red-detuned by $\Delta \simeq -2\Gamma$ from the $5S_{1/2}, F = 2 \rightarrow 5P_{3/2}, F = 3$ transition. A second grating-stabilized diode laser tuned to the $5S_{1/2}, F = 1 \rightarrow 5P_{3/2}, F = 2$ transition is used to injection-lock another laser diode which provides up to 30 mW of repumping light. The cooling and repumping laser beams are superposed and split into two beams which are subsequently circularly polarized. After widening the beams by telescopes to a beam waist of 13 mm, the beams are steered to the quartz cell which they pass perpendicular to each other and to the zero-field line of the magnetic field. They are then retro-reflected after having passed another quarter-wave plate, thus providing the third and forth beam of the MOT. We find that the resulting intensity imbalance between the ingoing and the retro-reflected beams does not significantly perturb the functioning of the trap. Typically, the trap is operated at a total rubidium background pressure of 3×10^{-7} mbar. It is located close to the entrance of a differential pumping tube, with a diameter $d = 7$ mm and a length $l = 450$ mm, capable of maintaining a pressure ratio of more than two orders of magnitude between the first quartz cell and the cell of the injecting MOT. The total distance between the first and the second MOT is $L \simeq 800$ mm.

We use two methods to study the properties of the 2D-MOT. By measuring the fluorescence of the injecting MOT, we obtain a signal which is proportional to the flux of atoms that is produced by the 2D-MOT and recaptured by the injecting MOT. Even though this quantity is the most important parameter for the next stage of the experiment, it does not allow to characterize the performance of the 2D-MOT in a quantitative and independent way. Therefore, to gather more information we perform absorption measurements on the beam of atoms that arrives in the glass cell of the recapturing MOT. For this purpose, we shine a probe laser beam perpendicular to the atomic beam into the glass cell of the recapturing MOT. The beam is resonant with the $5S_{1/2}, F = 2 \rightarrow 5P_{3/2}, F = 3$ transition, has a diameter of 1 mm and is circularly polarized. A weak magnetic field in the direction of the probe beam ensures that the atoms crossing the probe beam are optically pumped to the outermost Zeeman state. By measuring the absorption of the probe beam, we obtain the column density of the atomic beam as a function of the probe beam position (in the direction perpendicular to the atomic beam). Information about the velocity distribution of the atoms is obtained by performing time-of-flight measurements. After suddenly turning off the repumping laser of the 2D-MOT, we measure the atomic velocity dispersion by monitoring the absorption of the probe beam as a function of time. Note that this method works since the velocity distribution Δv is on the order the mean velocity $\bar{v}$ and since the distance between the probe beam and the 2D-MOT is large compared to the size of the MOT. In order to increase the signal-to-noise ratio of the measurement, we dither the frequency of the probe laser at 100 kHz and use a lock-in amplifier to measure the absorption.

4. Experimental results

For the 2D-MOT with circular beam profiles described in the previous section, we find that the number N of atoms recaptured by the injecting MOT increases approximately linearly as a function of the cooling laser power P when P was varied between 16 mW and 160 mW per beam. When we reduce the cooling volume of the trap by introducing knife edges which limit the beam size, N decreases dramatically in the case where the length of the trap is reduced while it is much less affected if the transverse beam size is reduced. It has already been observed and explained in Ref. [12] that elliptical beam profiles are advantageous for maximizing the atomic flux. Here, instead of using cylindrical lenses to create elliptical beams, we split each of the MOT beams into two beams before passing them through the telescopes. Each pair of beams is now passed through the glass cell side to side to each other so as to produce a 2D-MOT with elongated beam profiles (see Fig. 1). The laser power of the tapered amplifier can be arbitrarily repartitioned among the four beams, and we find that a maximum of recaptured atoms is observed for a configuration where the intensity of the two beams that are closer to the trap exit is lower than the intensity of the other two beams. The measurements presented in the following have been performed with this optimized configuration.

Absorption measurements of the atomic beam are done at a distance $L \simeq 800$ mm from the 2D-MOT. The maximum absorption is on the order of 0.7%. Even though the absorption signal is small, it allows to calibrate those measurements that take advantage of lock-in detection. The column density profile of the atom beam in Fig. 2 is recorded by scanning the probe beam vertically (i.e., in a direction perpendicular to the atomic beam). The full width at half maximum (FWHM) of about 10 mm is superior to the diameter d of the differential pumping tube so that one might wonder whether the transverse beam size could be limited by the tube. If the transverse size of the 2D-MOT was negligible and the spatial density of the atomic flux was homogeneous at the tube exit, the linear density profile would have the shape of a half circle with diameter $d_c = dL/l \approx 12.4$ mm, giving a FWHM of 10.8 mm. A finite transverse trap size and the velocity-dependence of the

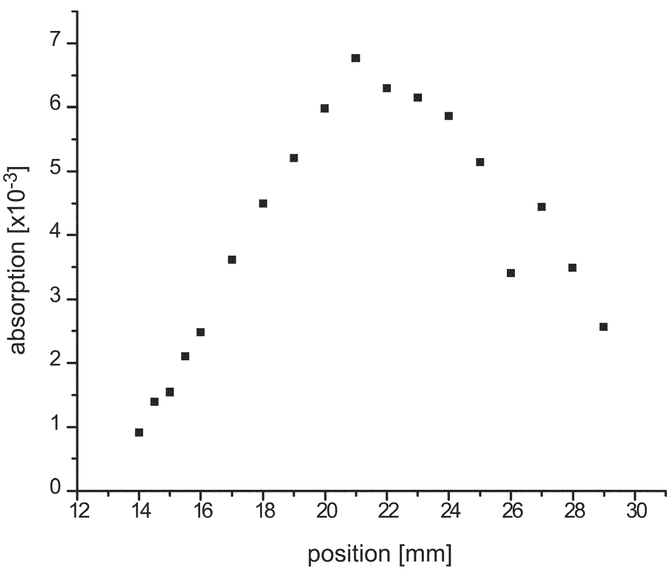

Fig. 2. Density profile of the atomic beam at a distance of 80 cm from the source.

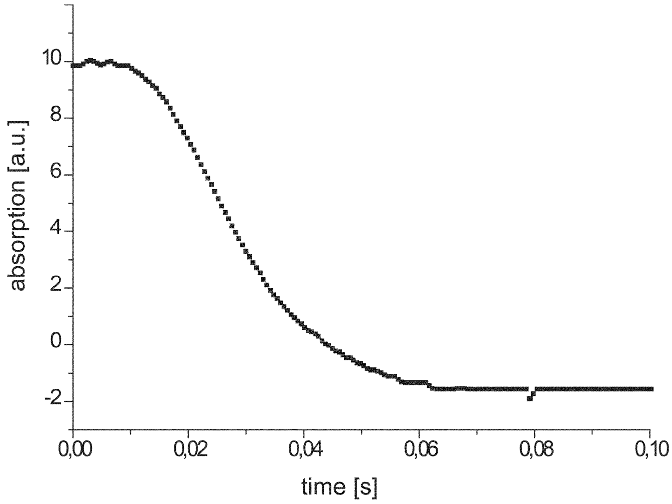

Fig. 3. Absorption signal obtained after switching off the 2D-MOT at $t = 0$.

beam profile due to gravity contribute to enlarge the beam size.

The velocity distribution of the atomic beam is obtained by rapidly switching off the repumping beam of the 2D-MOT and measuring the time-dependent absorption signal $s(t)$ as shown in Fig. 3.

The atomic flux density per velocity class $\rho_\Phi(v)$ is related to $s(t)$ by

$$\rho_\Phi(v) \propto t\frac{\mathrm{d}s}{\mathrm{d}t} \quad \text{with} \quad t(v) = L/v. \tag{3}$$

After calibrating the signal and integrating over the linear density profile, we obtain the atomic flux density which is shown in Fig. 4. The beam is found to have a mean velocity $\bar{v} = \int \mathrm{d}v\, v\rho_\Phi / \int \mathrm{d}v\, \rho_\Phi = 38$ m/s and a rather large velocity spread $\Delta v = \langle (v - \bar{v})^2 \rangle^{1/2} = 17$ m/s. The highest flux that we have measured was $\Phi \gtrsim 10^{10}$ atoms/s. This number includes atoms with velocities up to 100 m/s. The experimentally most relevant quantity is the atomic flux that the injecting MOT is able to recapture. The capture velocity that can be achieved strongly depends on the trap geometry as well as the laser power available for the injecting MOT and will typically lie in a range between 25 m/s and 40 m/s.

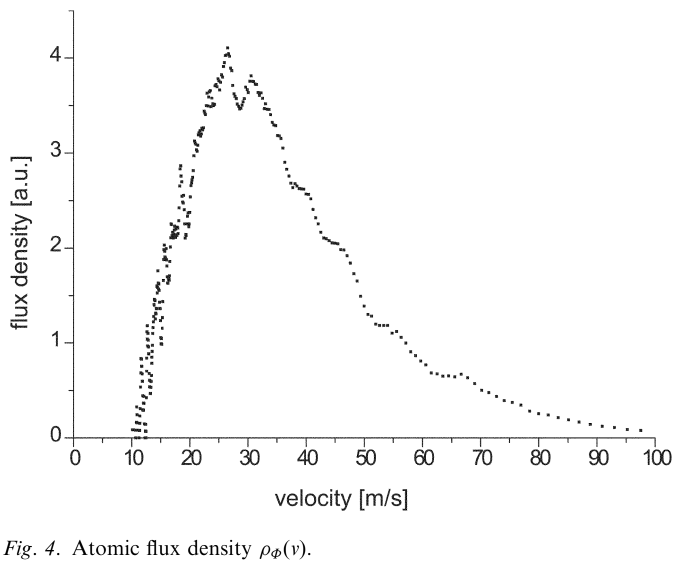

Fig. 4. Atomic flux density $\rho_\Phi(v)$.

The fraction of atoms with a velocity below 35 m/s is 50%, which corresponds to a useful flux of 5×10^9 atoms/s.

In this article, we have reported on the performance of a 2D-MOT similar to the one described in Refs. [11,12]. In our setup, we use two adjacent 2D-MOT which allows to maximize the atomic flux by redistributing the available laser power among the two traps. This source has been developed for loading a moving molasses MOT which serves to inject a cold and slow atomic beam into a magnetic guide.

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References

1. Chikkatur, A. P. *et al.*, Science **296**, 2193 (2002).
2. Mandonnet, E. *et al.*, Eur. Phys. J. D **10**, 9 (2000).
3. Schmiedmayer, J., Phys. Rev. A **52**, R13–R16 (1995).
4. Denschlag, J., Cassettari, D. and Schmiedmayer, J., Phys. Rev. Lett. **82**, 2014 (1999).
5. Goepfert, A. *et al.*, Appl. Phys. B **69**, 217 (1999).
6. Key, M. *et al.*, Phys. Rev. Lett. **84**, 1371 (2000).
7. Dekker N. H. *et al.*, Phys. Rev. Lett. **84**, 1124 (2000).
8. Teo, B. K. and Raithel, G., Phys. Rev. A **63**, 031402 (2001).
9. Sauer, J. A., Barrett, M. D. and Chapman, M. S., Phys. Rev. Lett. **87**, 270401 (2001).
10. Hinds, E. A. and Hughes, I. G., J. Phys. D: Appl. Phys. **87**, R119 (1999).
11. Dieckmann, K., Spreeuw, R. J. C., Weidemüller, M. and Walraven, J. T. M., Phys. Rev. A **58**, 3891 (1998).
12. Schoser, J. *et al.*, Phys. Rev. A **66**, 023410 (2002).
13. Barrett, T. E. *et al.*, Phys. Rev. Lett. **67**, 3483 (1991); Phillips, W. D. and Metcalf, H., Phys. Rev. Lett. **48**, 596 (1982).
14. Lu, Z. T. *et al.*, Phys. Rev. Lett. **77**, 3331 (1996).
15. Lee, K. I., Kim, J. A., Noh, H. R. and Jhe, W., Opt. Lett. **21**, 1177 (1996).
16. Williamson III, R. S., Voytas, P. A., Newell, R. T. and Walker, T., Opt. Express **3**, 111 (1998).
17. Arlt, J. J., Marago, O., Webster, S., Hopkins, S. and Foot, C. J., Opt. Commun. **157**, 303 (1998).
18. Wohlleben, W., Chevy, F., Madison, K. and Dalibard, J., Eur. Phys. J. D **15**, 237 (2001).
19. Cacciapuoti, L., Castrillo, A., de Angelis, M. and Tino, G. M., Eur. Phys. J. D **15**, 245 (2001).
20. Riis, E., Weiss, D., Moler, K. and Chu, S., Phys. Rev. Lett. **64**, 1658 (1990); Swanson, T., Silva, N., Mayer, S., Maki, J. and McIntyre, D., J. Opt. Soc. Am. B **13**, 1833 (1996); Chen, H. and Riis, E. Appl. Phys. B **70**, 665 (2000).
21. Cren, P., Roos, C. F., Aclan, A., Dalibard, J. and Guéry-Odelin, D., Eur. Phys. J. D **20**, 107 (2002).