C. R. Acad. Sci. Paris, t. 2, Série IV, p. 657–662, 2001
Atomes, molécules/*Atoms, molecules*

OPTIQUE ET INTERFÉROMÉTRIE ATOMIQUES
ATOM OPTICS AND INTERFEROMETRY

Experimental study of coupling Bose–Einstein condensates into weakly non-trapping and trapping states

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(Reçu le 1^er^ janvier 2001, accepté le 26 mars 2001)

Abstract. We study the production of an atom laser from a Bose–Einstein condensate using radio-frequency out-coupling. Single frequency coupling from the Bose–Einstein condensate leads to unstable production of an atom laser due to the extreme sensitivity of this process to magnetic field fluctuations. The extent of this experimental instability is quantified. Stable, repeatable production of an atom laser is achieved by the frequency modulation of the coupling, which forms a frequency comb across the condensate. Different regimes of modulated coupling are discussed. In addition the coupling of atoms into a weakly trapping state is studied. The oscillation frequency of this state in the vertical direction is measured. Preliminary results indicating qualitative difference between condensate and thermal cloud coupling are presented. © 2001 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS

cold atoms / Bose–Einstein condensate / output coupler / atom laser / quantum coherence

Étude du couplage de sortie d'un condensat vers un niveau libre et vers un niveau faiblement piégeant

Résumé. *Nous présentons la réalisation d'un laser à atomes à partir d'un condensat de Bose–Einstein grâce à lutilisation d'un coupleur radio-fréquence. Dans le cas d'un laser monomode (un seul coupleur radiofréquence), le couplage de sortie est très sensible aux fluctuations du champ magnétique qui piège le condensat. Une mesure des instabilités du laser permet alors de quantifier les fluctuations du champ magnétiques. Afin de rendre le couplage insensible aux fluctuations, nous avons ensuite utilisé un coupleur radio-fréquence modulé, qui crée de multiples coupleurs de sortie régulièrement espacés. Nous présentons finalement l'étude du couplage des atomes vers un état très faiblement piégé. L'évolution d'un condensat laché dans une telle cavité a pu être étudiée et a permis de déterminer la fréquence d'oscillation des atomes. Enfin, dans le cas d'un couplage faible (quasi-continu), il est possible de distinguer entre le couplage d'un condensat, intrinsèquement cohérent, et un nuage thermique. © 2001 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS*

Note présentée par Guy LAVAL.

S1296-2147(01)01191-X/FLA

atomes froids / condensat de Bose–Einstein / coupleur de sortie / laser à atomes / cohérence quantique

1. Introduction

Since the creation of the first dilute Bose–Einstein Condensate (BEC) [1] atom lasers sourced from them have been an important topic of study. Pulsed atom lasers have been realized by a variety of techniques, using: intense, pulsed, spin–flip radio frequency (RF) transitions [2], and gravity induced tunneling from an optically trapped condensate [3]. A quasi-continuous laser has been realized using Raman transitions [4] and a continuous atom laser, limited only by the depletion of the condensate, has been achieved by RF coupling under highly stable conditions [5]. These developments illustrate the atom lasers potential to form atomic beams of unprecedented brightness and coherence. There is therefore need to control precisely the production of the laser and to develop tools that characterize the laser. In this proceeding we discuss the stability requirements for the production of a continuous laser and demonstrate the production of a stable laser using a frequency comb. Preliminary results on coupling a fraction of the BEC and cold thermal atoms from the $|1,-1\rangle$ state into a weakly trapping state are also presented.

2. Atom laser

The experimental scheme used is described in detail elsewhere [6]. Briefly, a ^{87}Rb BEC with approximately $5 \cdot 10^5$ atoms is created in the $|1,-1\rangle$ (i.e. $F = 1,\ m_{\mathrm{F}} = -1$) state. The construction of the magnetic trap results in the production of a relatively large bias field as well as a large magnetic gradient in the quadrupole direction (vertical plane). Under these condition the contribution of the quadratic Zeeman effect makes the $|1,0\rangle$ and $|2,0\rangle$ states slightly anti-trapping and trapping respectively. We couple the BEC to one or the other state by using either a radio frequency (RF) or a microwave frequency.

Production of a continuous atom laser, as in [5], is done by coupling the atoms from the trapping $|1,-1\rangle$ state to the weakly anti-trapping $|1,0\rangle$ state. This is implemented using a RF of approximately 40 MHz. The frequency is relatively high due to the high bias field of 56 Gauss in our experiment. The RF power is adjusted such that the approximate estimation of the Rabi frequency for typical coupling parameters is about 1 kHz. The RF coupling is applied for a duration of about 20 ms.

Using a single radio frequency we can successfully couple atoms into the $|1,0\rangle$ state to produce an atom laser. However, the atom laser exhibits both intra-shot and shot-to-shot instabilities in the density of the out-coupled beam. In a similar experiment, continuous production of the atom laser has been demonstrated by Bloch et al. (1999) [5]. They achieve high stability in the laser output with a combination of magnetic shielding and stable current supply, which ensure magnetic field stability. Our experiment is not stabilized to the same extent and therefore instabilities of the magnetic field can result in the laser density fluctuations. [1]

To quantify the fluctuation of the magnetic trapping potential we study the depletion of the condensate versus the RF out-coupling frequency. The total number of atoms in the combined thermal cloud and condensate is approximately $1 \cdot 10^6$ of which the condensate fraction is about 50%. Varying the frequency of the RF coupling, we measure the atoms remaining in $|1,-1\rangle$ state after 10 ms of out-coupling. This measurement does not discriminate between the thermal cloud and the condensate atoms in $|1,-1\rangle$ (*figure 1*). The measured width of the out-coupled atoms in our case is approximately 80 kHz at the threshold. The spectral width for out-coupling a condensate is given by its spatial extent in the vertical direction because of the variation in the gravitational potential energy across it. The frequency width is therefore given by $\Delta\nu = M_{\mathrm{Rb}} g \Delta s/\hbar$, where M_{Rb} is the mass of ^{87}Rb, g the acceleration due to gravity, Δs the spatial extent of the condensate and $\hbar$ the Planck constant. Similar considerations hold for the thermal atoms in the trap. The calculated spectral width for the condensate is approximately 10 kHz and the thermal cloud has a calculated one sigma width of 11 kHz. Thus the observed experimental width of

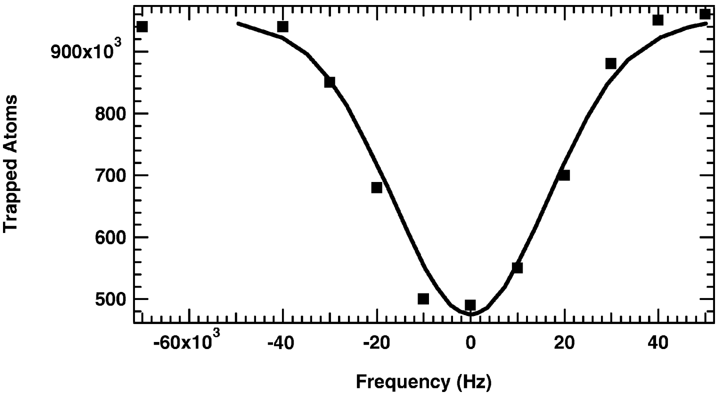

Figure 1. The filled squares represent the depletion of the condensate and thermal atoms from the $|1,-1\rangle$ state as a function of out-coupling frequency. The frequency axis has been centered at the point for maximum out-coupling. The line is the convolution of the atomic density profile in $|1,-1\rangle$ with a normal distribution of one sigma width 15 kHz, representing the fluctuations in the magnetic field bias.

80 kHz is much larger than the expected width due to the condensate and thermal cloud (approximately 30 kHz). The present measurement is therefore a convolution of the condensate and thermal cloud widths, with the experimental instabilities, which has the effect of broadening the depletion profile.

The primary source of instability in our experiment is from fluctuations in the trapping magnetic field, which gives rise to a corresponding change in the resonance condition for optimal output coupling. The efficiency of coupling is sensitive to these instabilities when the amplitude of the magnetic field fluctuations is comparable to or larger than the spectral width of the condensate. In order to estimate the fluctuation in the magnetic trapping field, which corresponds to shift in out-coupling frequency, we assume that it is consistent with a normal distribution. The convolution of a normal distribution with a one sigma value of 15 kHz, with the calculated spectral density profiles of the condensate and thermal cloud gives good agreement with the measured depletion of atoms in $|1,-1\rangle$ (*figure 1*). At this value we agree well with both the FWHM (40 kHz) of the depletion curve as well as with the lower and upper thresholds for out-coupling (80 kHz). From this we can conclude that the amplitude of the fluctuations have a spectral width (two sigma) of approximately 30 kHz. Such an instability in the amplitude of the trapping magnetic field imposes severe limitations on the ability to produce an atom laser with uniform density distribution, using a single RF, making other means for is production necessary.

To circumvent the instability we produce an atom laser using a frequency comb instead of a single frequency, thus countering the magnetic field fluctuations. The frequency comb is created by frequency modulating the out-coupling RF, about the frequency of maximum output coupling ν_c (carrier frequency). The expression for the modulation is $\nu_\mathrm{RF} = \nu_\mathrm{c} + \nu_\mathrm{BW} f(\nu_\mathrm{m} t)$, where ν_BW is the frequency bandwidth of the modulation (typical experimental value is 100 kHz) about ν_c and a triangular modulation function $f(\nu_\mathrm{m} t)$. The power of the RF comb is adjusted for individual comb elements to be in the weak coupling regime.

In the time domain picture of frequency modulation the frequency of the carrier wave (ν_c) varies across the bandwidth (ν_BW) twice every modulation cycle. As the modulation frequency is varied three distinct regimes of output coupling are evident from the experimental data. At low modulation frequencies (i.e. $\nu_\mathrm{m} \leqslant 1000$ Hz), atoms from the condensate are coupled out each time the frequency modulation crosses the instantaneous resonance frequency (twice every cycle). The output coupled atoms are non overlapping and form distinct condensate replicas (*figure 2a*). On increasing the modulation frequency, the rate of output from the condensate increases, to give a quasi-continuous output (*figures 2b* and *2c*). At still higher modulation frequency we have the overlapping of successively out-coupled atoms from the condensate, over a considerable spatial extent as they fall under the combined influence of the gravitational and weakly non-trapping magnetic potential. In this regime we can see non uniformity of the imaged out-coupled atoms, which may be attributed to the interference between successively out-coupled atoms from the condensate

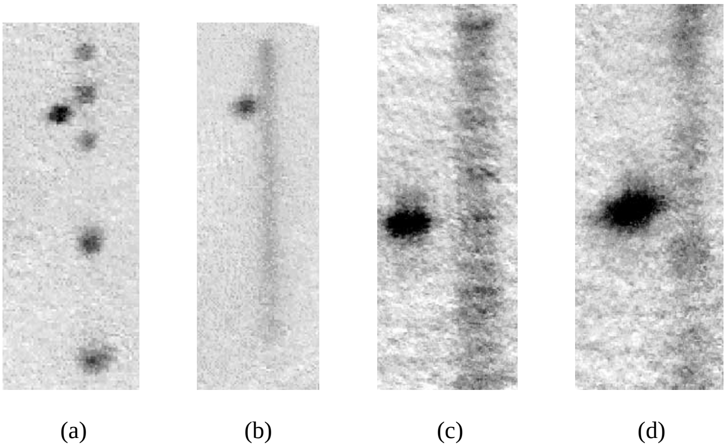

Figure 2. The different regimes of comb coupling. (a) At a small modulation frequency ($\nu_{\rm m}$) of 230 Hz. (b) Quasi-continuous coupling with $\nu_{\rm m} = 2000$ Hz. (c) Quasi-continuous coupling with magnified imaging at $\nu_{\rm m} = 3000$ Hz. (d) Unstable coupling at $\nu_{\rm m} = 17\,000$ Hz in the magnified imaging system. Cutting the magnetic field just before imaging results in the spatial separation of the condensate and the atom laser.

in the fluctuating magnetic field. In another measurement, on changing the bandwidth of the frequency comb, the out-coupling is seen to be reproducible at and above a $\nu_{\rm BW}$ value of approximately 40 kHz, whereas below this value it becomes unstable from shot-to-shot. This is consistent with the full width at half maximum of the stability measurement (*figure 1*) and gives us an independent measure of the magnetic field fluctuations.

In the frequency domain the three regimes of out-coupling can be understood as follows. If the frequency comb is very dense, which is the case at small modulation frequencies ($\nu_{\rm M}$ much less than the condensate spectral width), we can expect to see interference between the matter waves coupled out of different spatial regions of the condensate and this behaviour manifests in the appearance of discrete atom-bunches in time (*figure 2a*). A crude simulation of the time interval between successive atom-bunches can be done by fourier transforming the product of a frequency comb with appropriate phase relations and the Thomas–Fermi condensate shape. Such a simulation is in rough agreement with the observed data. As the modulation frequency increases the temporal spacing between the out-coupled atom bunches decreases and at $\nu_{\rm M}$ approximately few thousand Hz all the discreteness in the out-coupling disappears within the limits of the imaging system and a quasi-continuous beam of out-coupled atoms is seen (*figures 2b* and *2c*). On increasing the comb frequency still further we achieve the condition that one or less comb teeth are available for output coupling and we revert to the situation analogous to single frequency coupling, where the instabilities in the magnetic field start affecting the out coupling (*figure 2d*).

3. Atom ‘cavity’

It is also interesting to study the coupling of a condensate in an weakly trapping state that is much larger in spatial extent than the condensate. Such a state can be considered as an atomic cavity and can be used to study the dynamics of coherent evolution of the atoms from the condensate. In our experiment the $|2,0\rangle$ state of the $F = 2$ manifold is such a state. Atoms are coupled directly from the $|1,-1\rangle$ condensate state to the cavity using a single microwave frequency of approximately 6.8 GHz.

In our experiment the measured frequency for the BEC state in the vertical direction is $\nu_{\perp,\rm BEC} = 132.5$ Hz, with an experimental uncertainty of ± 0.25 Hz. Using this value to establish the magnetic gradient field of the trap we estimate the trap frequency of the cavity state in the vertical direction as $\nu_{\perp,\rm cav} \approx 29$ Hz, with a few percent accuracy. Gravity shifts the trap centers for the various magnetic sublevels by different amounts. The cavity state sags vertically by $z_{\rm cav} = g/(2\pi\nu_{\perp,\rm cav})^2 \approx 310$ µm. By comparison, the condensate shifts down by $z_{\rm BEC} \approx 15$ µm, giving a relative shift of 300 µm. Since the atoms are coupled from the highly localized condensate in the vertical direction into the cavity state by a microwave photon, they are coupled to a region away from the cavity centre. The atoms are therefore coupled in the high lying energy levels of the cavity state.

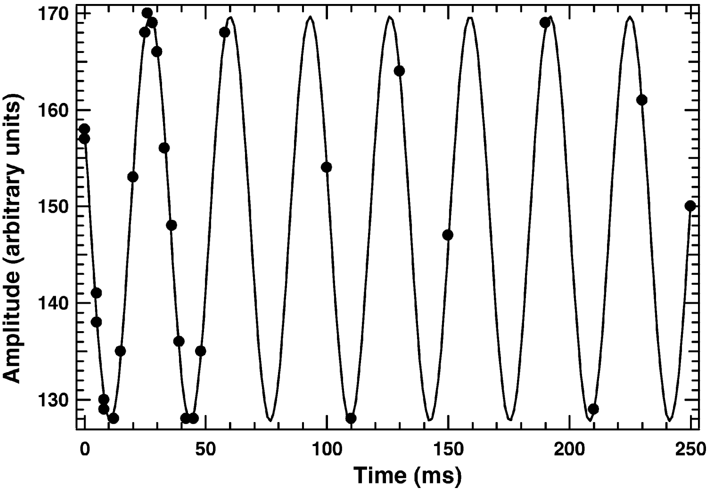

Figure 3. Measurement of the period of oscillation of the atoms coupled into the $|2, 0\rangle$ (cavity) state. The filled circles are the data points while the line through them is a single frequency sinusoidal fit which gives a cavity frequency of 30.3 Hz (period $= 33$ ms). The statistical error on the measured position of the atoms in the cavity is at most one division along the amplitude axis for each point.

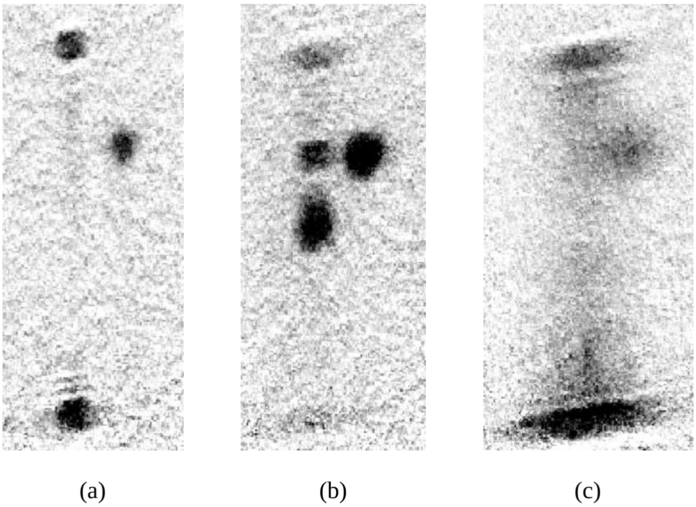
(a) (b) (c)

Figure 4. Atoms coupled into the cavity state from the $|1, -1\rangle$ state. (a) An over evaporated condensate coupled into the cavity state. (b) A pure condensate in the cavity state where we see a distinct structures in the spatial density distribution of atoms while (c) is the case of thermal cloud coupling into the cavity state resulting in a uniform spatial distribution of atoms.

To determine the cavity state frequency, the oscillation of atoms coupled into the cavity was measured as a function of time. For this experiment a fraction of the atoms were out-coupled from the condensate into the cavity state by a strong, resonant microwave pulse of short duration (2 ms). The cavity state frequency was measured by studying the position of centre of mass of the atomic cloud as shown in *figure 3*. The fitted value of the oscillation period is found to be 33 ms corresponding to an oscillation frequency of 30.3 Hz. This value agrees with the the estimated trap frequency given above. The goodness of fit for a single frequency sinusoid fit over several periods of oscillation in the cavity indicates that we are in the region of the cavity where deviations from the simple harmonic nature of the oscillations are small, despite its relatively large spatial extent. The one sigma error on the fit value is under 0.1% in frequency.

As we lower the microwave power (i.e. go to weaker coupling intensities) and increase the coupling time of the atoms from the BEC, structures are observed in the cavity state (*figures 4a* and *4b*). These structures represent a non uniform spatial density distribution of atoms in the cavity state. By contrast, coupling from a cold thermal cloud results in a uniform density distribution of atoms in the cavity (*figure 4c*). The above results are preliminary as systematic study is limited by instability in the bias field. Numerical integration of the Gross–Pitaevskii equation yields structures similar to those observed in the cavity state. This suggests that the structures in the cavity state are signature of the coherence of a BEC, while lack of structure for the thermal cloud is due to its lack of coherence.

4. Conclusions

We have demonstrated a method for continuous output coupling of a condensate into a non trapping state which overcomes the problem of small fluctuations in the trapping magnetic field. The method involves the modulation of the frequency of out-coupling over a bandwidth larger than the bandwidth of the fluctuation. Various regimes of operation for this method have been explored and discussed. In addition certain preliminary results of coupling the atoms into a extended, weakly trapping state have been discussed. Coupling into this state seems to show different behaviour for the condensate as opposed to a thermal cloud.

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[1] Since the measurements reported here we have successfully suppressed the fluctuations in the magnetic bias field using a better stabilized power supply, which enables us to produce a continous atom lasers using single radio frequency.

References

[1] Anderson M.H. et al., Science 269 (1995) 198;
Bradley C.C. et al., Phys. Rev. Lett. 75 (1995) 1687;
Davis K.B. et al., Phys. Rev. Lett. 75 (1995) 3969;
Bradley C.C. et al., Phys. Rev. Lett. 78 (1997) 985.
[2] Mewes M.-O. et al., Phys. Rev. Lett. 78 (1997) 582.
[3] Anderson B.P., Kasevich M., Science 282 (1998) 1686.
[4] Hagley E.W. et al., Science 283 (1999) 1706.
[5] Bloch I. et al., Phys. Rev. Lett. 82 (1999) 3008.
[6] Desruelle B. et al., Phys. Rev. A 60 (1999) R1759.