Title	Observing the profile of an atom laser beam
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Publication date	2005
Original citation	Köhl, M., Busch, T., Mølmer, K., Hänsch, T. W. and Esslinger, T. (2005) 'Observing the profile of an atom laser beam', Physical Review A, 72(6), 063618 (4pp). doi: 10.1103/PhysRevA.72.063618
Type of publication	Article (peer-reviewed)
Link to publisher's version	https://journals.aps.org/pra/abstract/10.1103/PhysRevA.72.063618 http://dx.doi.org/10.1103/PhysRevA.72.063618 Access to the full text of the published version may require a subscription.
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PHYSICAL REVIEW A **72**, 063618 (2005)

Observing the profile of an atom laser beam

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(Received 31 August 2005; published 23 December 2005)

We report on an investigation of the beam profile of an atom laser extracted from a magnetically trapped ^{87}Rb Bose-Einstein condensate. The transverse momentum distribution is magnified by a curved mirror for matter waves and a momentum resolution of 1/60 of a photon recoil is obtained. We find the transverse momentum distribution to be determined by the mean-field potential of the residing condensate, which leads to a nonsmooth transverse density distribution. Our experimental data are compared with a full three-dimensional simulation of the output coupling process and we find good agreement.

DOI: 10.1103/PhysRevA.72.063618 PACS number(s): 03.75.Pp, 07.77.Gx, 32.60.+i

Similar to the principle of an electron microscope, atomic matter waves can be utilized to resolve structures on the nanometer scale [1]. In contrast to electrons, atoms exhibit an extremely small de Broglie wavelength even at low energies. This could allow for the gentle detection of nanoscopic textures provided that atomic beams can be focused to a diffraction limited spot size. Such an undertaking seems achievable with the availability of Bose-Einstein condensates as nearly perfect matter wave sources. From Bose-Einstein condensates well collimated and bright atom laser beams have been extracted [2–8] which by far exceed thermal beams regarding spatial and temporal coherence [9–11].

Similar to laser operation in optics, the beam profile of an atom laser is determined by the laser cavity and the beam extraction from the cavity. Investigating the beam properties for coherent matter waves is a difficult undertaking and so far no deviation from the ideal behavior has been detected. Theoretically, the longitudinal [12–14] and transverse [15] mode properties of beams have been analyzed. Experimentally, the temporal coherence of atom lasers [10] has been observed and the divergence angle [6] was measured, however, without revealing the actual beam profile. Here we present an experimental investigation of the transverse momentum distribution of an atom laser beam and show that it is influenced by the specific nature of the output coupling mechanism.

A common method to extract atom laser beams from condensates in magnetic traps is to continuously transfer a small fraction of the trapped atoms into an untrapped state with a vanishing magnetic moment [5,6,8]. The transferred atoms no longer feel the confining trapping potential and are accelerated by gravity, forming a downward propagating beam. Since the output coupling happens within the condensate, the beam will initially experience the repulsive mean-field potential of the residing condensate. This acts as an inhomogeneous refractive index profile and will influence the transverse momentum distribution [6,15].

To quantify the influence of the residual condensate on the transverse momentum distribution, let us consider a condensate in the anisotropic harmonic trapping potential $V_c = (m/2)[\omega_\perp^2(x^2+z^2)+\omega_y^2 y^2]$ with the z axis oriented vertically. Since the force exerted by the condensate on the beam is proportional to the gradient of the condensate density, we will assume first that $\omega_\perp > \omega_y$ and restrict ourselves to the two-dimensional situation in the x-z plane, where both trapping frequencies are high. Upon transfer into an untrapped atomic state, the atoms are subjected to the gravitational and the (repulsive) condensate mean-field potential only. In the Thomas-Fermi approximation this potential is given by

$$V = mgz + \begin{cases} \mu\left(1 - \dfrac{x^2+z^2}{r_{\mathrm{TF}}^2}\right) & \text{if } x^2+z^2 < r_{\mathrm{TF}}^2, \\ 0 & \text{otherwise}, \end{cases} \qquad (1)$$

where m denotes the atomic mass, g the gravitational acceleration, μ the chemical potential and r_{TF} the Thomas-Fermi radius of the strongly confined x and z direction of the condensate. The output coupled atoms experience a force proportional to the density gradient at their respective position.

In the two dimensional setting the output coupling of the atoms takes place on a circle of constant magnetic field, which is defined by the resonance condition for the spin-flip transition. Due to the gravitational force, however, the center of the condensate is displaced from the minimum of the magnetic field by an amount $z_0 = g/\omega_\perp^2 > r_{\mathrm{TF}}$. In fact, the output coupling region intersects with the condensate on an almost horizontal slice. The forces due to the inhomogeneity of the condensate density profile mainly affect the strongly confined transverse direction (see Fig. 1).

If the size of the repulsive mean-field potential would not be finite, but simply an untruncated inverted harmonic oscillator potential it would act as a diverging atom optical element [6], since the atoms would always experience a force proportional to their distance from the center of the potential. We have recently argued that the truncation of the inverted

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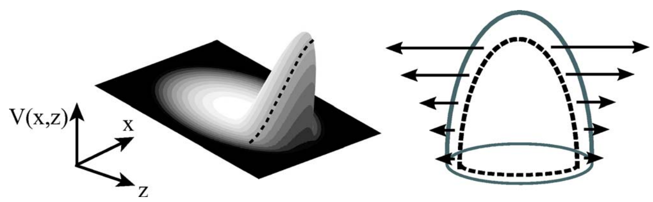

FIG. 1. (Color online) Left: The combined inverted parabola potential caused by the trapped Bose-Einstein condensate and the gravity potential acting on the $|F=1,m_F=0\rangle$ atoms in the atom laser beam. The dashed line indicates the region where the resonance condition is fulfilled and output coupling takes place. Right Schematic density profile of the trapped condensate (solid line) and the output coupled atoms (dashed line). The arrows indicate the transverse velocity that the output coupled atoms gain due to roll off from the mean field potential of the remaining condensate.

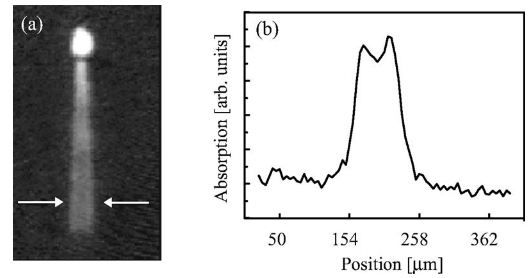

FIG. 2. (a) Atom laser beam extracted from a compressed Bose-Einstein condensate. The double peak structure of the beam is clearly visible. The height of the image is 780 μm. (b) Cut through the atomic density distribution at the position indicated by the arrows.

parabola potential of the condensate mean-field leads to interference fringes in the transverse direction of the atom laser beam [15]. Two atoms starting at rest from *different* transverse locations within the horizontal slice of the output coupling region may end up with different velocities at the *same* transverse position outside the condensate after a certain time, which leads to quantum mechanical interference. Therefore, the far-field distribution is not just simply a scaled copy of the initial density distribution.

We have experimentally investigated the transverse momentum distribution of an atom laser beam output coupled from a magnetically trapped Bose-Einstein condensate. We start out by producing Bose-Einstein condensates of about 5×10^5 ^{87}Rb atoms in a quadrupole-Ioffe configuration (QUIC) trap [16] in the $|F=1,m_F=-1\rangle$ hyperfine groundstate by evaporative cooling. The initial trapping frequencies are $\omega_\perp=2\pi\times110$ Hz in the radial and $\omega_y=2\pi\times14$ Hz in the axial direction, so that our condensate is cigar shaped. After formation of the condensate we increase the radial trapping frequency to $\omega_\perp=2\pi\times200$ Hz over a time scale of one second. Due to the magnetic field geometry of the QUIC trap and the nonlinear permeability of the μ metal enclosure the axial confinement is weakened in this process leading to a trap frequency of $\omega_y=2\pi\times11$ Hz. The final chemical potential is 2.5 kHz and the Thomas-Fermi radius in the radial direction is 3.7 μm. The atom laser beam is then extracted from the condensate by continuous output coupling [5]; a weak monochromatic radio-frequency field transfers atoms locally from the magnetically trapped condensate into the untrapped state $|F=1,m_F=0\rangle$ in which the atoms propagate downward due to gravity and form a collimated beam.

An absorption image of an atom laser beam is shown in Fig. 2(a). The line of sight is chosen along the symmetry axis of the cigar-shaped condensate. The atom laser beam exhibits a two peak structure in the transverse direction. A horizontal cut through the density distribution of the atom laser beam 500 μm below the Bose-Einstein condensate clearly reveals this structure [see Fig. 2(b)]. This indicates that the transverse momentum distribution of the atom laser is not a scaled copy of the condensate wave function and it is not sufficiently well described by just a divergence angle. The difference compared to the results reported in [6] we attribute to the experimental settings. The direction of observation in our experiment is chosen along the symmetry axis of the condensate whereas in [6] the line of sight was at an angle of 55° with respect to the symmetry axis which might have averaged out details of the density distribution. In the direction of view orthogonal to the symmetry axis of the condensate we find no modification of the atom laser density. This is consistent with the substantially smaller curvature of the mean-field potential along this axis. Moreover, in our experimental configuration the confining magnetic potential is stronger and correspondingly the mean-field curvature is more pronounced.

For a more detailed investigation of the structure of the beam a higher momentum resolution in the transverse direction is desirable. We accomplish this by employing a matter wave mirror in a curved mirror configuration such that the mirror acts as a "magnifying glass" for the atom laser beam. The principle of the atom mirror is to switch the interaction between the atoms in the atom laser beam and an external magnetic field on and off by an optically induced spin-flip transition [17]. A pair of phase-coherent laser beams drive a two-photon hyperfine Raman transition between the magnetically untrapped state $|F=1,m_F=0\rangle$ and the magnetically trapped state $|F=2,m_F=1\rangle$ approximately 500 μm below the position of the Bose-Einstein condensate. After the atoms are transferred into the $|F=2,m_F=1\rangle$ state by adiabatic passage on their way downward they are reflected off the inhomogeneous field of the magnetic trap. On their way upward they pass through the Raman lasers again and are coherently transferred back into the initial state $|F=1,m_F=0\rangle$ after which they move ballistically in the gravitational potential. The efficiency of this reflection process is almost 100% [17], the mirror preserves the coherence of the incident atom laser beam [10] and it operates continuously, as opposed to curved mirrors for Bose-Einstein condensates based on pulsed magnetic fields [18].

The "surface" of the mirror is defined by the lines of constant magnetic field, which are approximately concentric cylinders with the condensate being displaced only slightly from their center. In light optics one would expect a wave emerging from the center of the curved mirror being reflected back onto itself. In matter wave optics the situation is different. The gravitational acceleration collimates the atom laser beam since after half a millimeter dropping distance in the gravitational potential the longitudinal velocity

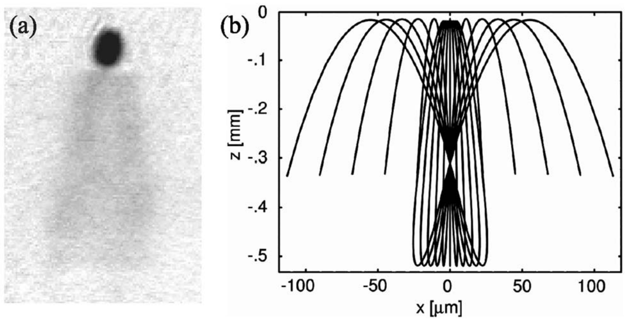

FIG. 3. (a) Atom laser after reflection by the curved mirror. The height of the image is 780 μm and it is taken 33 ms after starting the output coupling process including a 3 ms ballistic expansion for the Bose-Einstein condensate. (b) Classical trajectories of atoms being reflected from the curved matter wave mirror. After reflection the atoms laser is beam is focused about 300 μm below the Bose-Einstein condensate. The evolution is shown up to 30 ms after the start of output coupling.

($\approx$10 cm/s) has already overcome the transverse velocity spread by more than one order of magnitude. The reflected atom laser beam is therefore focused at a distance about half the radius of curvature away from the mirror [see Fig. 3(b)]. Due to the axial symmetry of the magnetic trapping potential, the focusing occurs only in one transverse direction. During the reflection from the curved potential the transverse momentum changes by a factor −2.6, as calculated from a simulation of the classical trajectories. The atomic density distribution is imaged by absorption imaging 20–30 ms after the reflection of the atoms and the beam is widened approximately by a factor of 6. The amplification factor is determined by the longitudinal velocity and the transverse location of the reflecting point of the atoms which is proportional to the initial transverse velocity. It is crucial for the application of this momentum magnification scheme that the beam is already Fourier separated in the transverse direction (i.e., the transverse velocity is a unique function of the transverse coordinate) when it enters the mirror. Otherwise the curved mirror will modify the far field evolution of the atom laser beam.

The achieved momentum resolution in the transverse direction is very high. Given the spatial resolution of the imaging system of 5.2 μm, the momentum magnification by a factor 2.6 and observation 20 ms after the atoms were reflected off the mirror, one obtains 0.1 mm/s equivalent to 1/60 photon recoil.

The transverse atomic density distribution 20 ms after reflection from the Raman mirror is shown in Figs. 4(a)–4(d) for different extraction regions inside the Bose-Einstein condensate. The traces differ by 2 kHz in output coupling frequency or equivalently by 1 μm in output coupling position. For output coupling from the bottom of the condensate [Fig. 4(d)] the transverse momentum distribution is a single peaked function. This results from the short interaction time of the atom laser beam with the mean-field potential. When the extraction of the atom laser beam is performed closer to the center of the condensate the interaction time and the mean-field potential increase which leads to a larger trans-

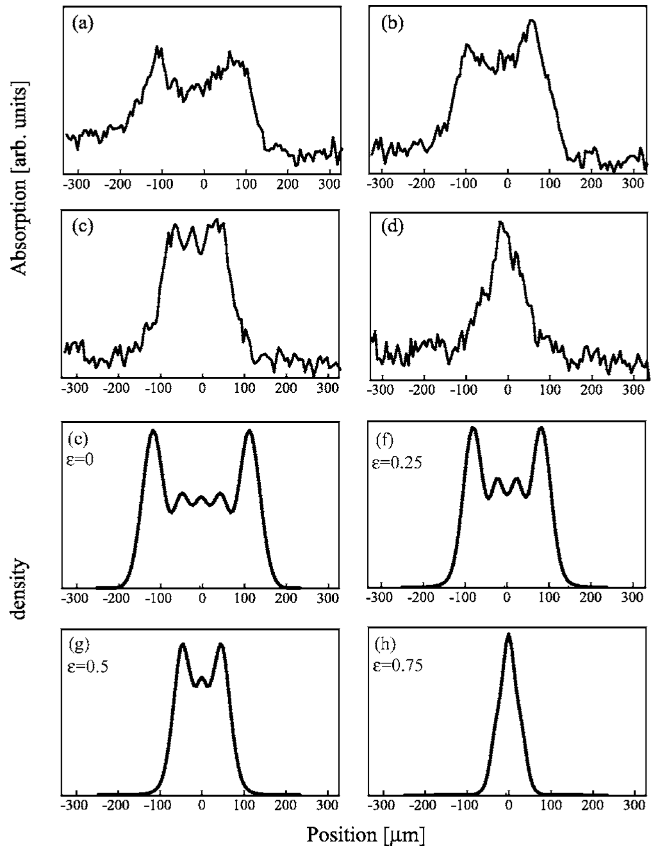

FIG. 4. Transverse density distribution of an atom laser beam after momentum magnification by the curved mirror. The profiles correspond to different output coupling regions within the Bose-Einstein condensate [top (a) to bottom (d)]. The difference in the output coupling frequency is 2 kHz between each slice [(a)–(d)] corresponding to 1 μm steps of the vertical extraction point. The density distribution is evaluated 250 μm below the position of the condensate. (e)–(h) Density profiles from a full three dimensional calculation for various output coupling positions $x_c = x_0 - \epsilon r_{\mathrm{TF}}$, corresponding approximately to the experimental data. The density is averaged along the long axis of the condensate, which takes into account the effect of the absorption imaging. Displayed is the far field density distribution as given by the Fourier transform of the density well below the condensate. The momentum distribution has been converted into position space according to the classical trajectories shown in Fig. 3(b).

verse momentum spread of the beam. The apparent noise on the density profiles which masks finer details of the interference fringes comes from the very low densities of the expanded atom laser beam. The optical density is lowered by the same factor of 6 as compared to conventional atom laser beams as the momentum resolution is enhanced. Working at a higher atomic flux or integrating over several repetitions of the same experiment could improve on the signal to noise ratio.

We have compared the measured traces with a full, three-dimensional numerical simulation of the output coupling process. Since the curvature of the mean field potential is comparatively small along the axial direction, no significant dynamics in the y direction is observed as expected. At the same time the dynamics in the x direction strongly scales with the exact location along the symmetry axis, due to the inhomogeneous density of the condensate. While the distributions for a single, fixed y value shows an interference pattern with high visibility [15], the integration along the line-of-sight averages out most of these pronounced two-dimensional interference fringes. In Figs. 4(e)–4(h) we show the calculated patterns which show a good qualitative agreement with the experimentally observed density distributions.

In the present configuration after reflecting off the curved mirror we obtain a very tight focus for the atom laser beam with a waist below the resolution limit of detection optics. We focus the atom laser beam with an f number [19] of approximately 3. With this low f-number and the inherently short de Broglie wavelength of a matter wave beam we estimate a focal spot size in the 100 nm regime and correspondingly a high atomic densitiy in the focus may be obtained. Given the the repulsive interactions between the rubidium atoms, a self-defocusing of the atom laser beam due to mean-field repulsion could be expected. However, with the present atomic density in the beam of about 10^{11} cm^{-3} and for an (assumed) diffraction limited spot size the density gradient is too small to lead to a significant self-defocusing. We estimate that for an initial beam density of 10^{14} cm^{-3} and focusing in both transverse directions the self-defocusing effect would become comparable to the usual mean-field expansion of a condensate, which could be easily detected. This regime of nonlinear matter wave propagation at high intensities would be very interesting to study since principal analogies with the propagation of high-intensity laser beams in nonlinear optical media exist. For atomic beams however, the nonlinearity is an intrinsic property of the beam.

In conclusion, we have studied the influence of the mean field potential of a Bose-Einstein condensate on the transverse momentum distribution of an atom laser beam. Using a curved matter wave mirror, we have magnified the transverse momentum distribution and obtained a momentum resolution of 1/60 photon recoil. The presented results indicate important consequences for the production and the properties of atom laser beams. In order to extract atom laser beams with a narrow transverse momentum spread, the interaction of the atoms with the mean-field of the remaining condensate has to be minimized. This might be achieved by performing the output coupling at the very bottom of the Bose-Einstein condensate or by reducing the condensate density. An alternative approach may also be the extraction of atom laser beams from an interaction-free Bose-Einstein condensate in the vicinity of a Feshbach resonance [20]. Since the transverse mode of the atom laser beam results from the interaction of the atoms with a time-independent conservative potential, one may—in principle—be able to compensate the momentum spread of the beam by a suitably shaped atom optical element. Since high quality, short focal length lenses for neutral atoms are very difficult to realize, focusing atom lasers with a curved mirror seems to be a promising alternative.

Note added in proof: Recently, a similar result has been report [21].

This work has been supported in part by DFG and the Danish research council, BEC 2000+, and benefited from discussions during the KITP Quantum Gases Program, Santa Barbara, California 2004.

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