Observing the Profile of an Atom Laser Beam

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We report on an investigation of the beam profile of an atom laser extracted from a magnetically trapped $^{87}\text{Rb}$ 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 non-smooth transverse density distribution. Our experimental data are compared with a full 3D simulation of the output coupling process and we find good agreement.

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Similar to the principle of an electron microscope, atomic matter waves could be utilized to resolve structures on the nanometer scale\textsuperscript{[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\textsuperscript{[2, 3, 4, 5, 6, 7, 8]} which by far exceed thermal beams regarding spatial and temporal coherence\textsuperscript{[3, 10, 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\textsuperscript{[12, 13, 14]} and transverse\textsuperscript{[15]} mode properties of beams have been analyzed. Experimentally, the temporal coherence of atom lasers\textsuperscript{[10]} has been observed and the divergence angle\textsuperscript{[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 the gravitational force, forming a downwards propagating beam. The transferred atoms experience the gravitational acceleration on the mean-field potential of the residing condensate. This acts as an inhomogeneous refractive index profile and will influence the transverse momentum distribution\textsuperscript{[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 $V_{c} = \langle m/2 \rangle [\omega_{x}^{2} (x^{2} + z^{2}) + \omega_{y}^{2} y^{2}]$ 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 (beating) potential. In the Thomas-Fermi approximation this potential is given by

\begin{equation}
V = mgz + \begin{cases} 
\mu \left( 1 - \frac{x^{2} + z^{2}}{r_{\text{TF}}^{2}} \right) & \text{if } x^{2} + z^{2} < r_{\text{TF}}^{2}, \\
0 & \text{else},
\end{cases}
\end{equation}

where $m$ denotes the atomic mass, $g$ the gravitational acceleration, $\mu$ the chemical potential and $r_{\text{TF}}$ 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 $z_{0} = g/\omega_{\perp}^{2} > r_{\text{TF}}$. In fact, the output...
monochromatic radio-frequency field transfers atoms locally
the condensate by continuous output coupling [5]: a weak
state from the magnetically trapped condensate into the untrapped
wards due to gravity and form a collimated beam.

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 parabola
potential of the condensate mean-field leads to interference
fringes in the transverse direction of the atom laser beam [15].

We have experimentally investigated the transverse momen-
tum 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 \times 10^5^{87} \text{Rb} atoms in a Quadrupole-Ioffe configura-
tion (QUIC) trap [16] in the |F = 1, m_F = −1⟩ hyperfine ground-
state by evaporative cooling. The initial trapping frequencies
are \omega_{\perp} = 2\pi \times 110 \text{ Hz} in the radial and \omega_y = 2\pi \times 14 \text{ Hz} in the
axial direction, so that our condensate shape is cigar-shaped.

An absorption image of an atom laser beam is shown in
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 \mu \text{m}. (b) Cut through the
atomic density distribution at the position indicated by the arrows.

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

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After formation of the condensate we increase the radial trapping
frequency to \omega_{\perp} = 2\pi \times 200 \text{ Hz} over a time scale of 1
second. Due to the magnetic field geometry of the QUIC-trap
and the nonlinear permeability of the \mu-metal enclosure the
axial confinement is weakened in this process leading to a trap
frequency of \omega_y = 2\pi \times 11 \text{ Hz}. The final chemical potential
is 2.5 kHz and the Thomas-Fermi radius in the radial direction
is 3.7 \mu \text{m}. The atom laser beam is then extracted from the
condensate by continuous output coupling [8]: a weak
monochromatic radio-frequency field transfers atoms locally
from the magnetically trapped condensate into the untrapped
state |F = 1, m_F = 0⟩ in which the atoms propagate down-
wards due to gravity and form a collimated beam.

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A pair of phase-coherent laser beams drive a two–photon hyperfine Raman transition between the magnet-
ically untrapped state |F = 1, m_F = 0⟩ and the magnetically
trapped state |F = 2, m_F = 1⟩ approximately 500 \mu \text{m} below the
position of the Bose-Einstein condensate. After the atoms
are transferred into the |F = 2, m_F = 1⟩ state by adiabatic
passage on their way downwards they are reflected off the in-
homogeneous field of the magnetic trap. On their way up-
wards they pass through the Raman lasers again and are coher-
ently transferred back into the initial state |F = 1, m_F = 0⟩
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 Fig. 4(a)-(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 transverse 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 the integration along the line-of-sight averages out most of these pronounced two-dimensional interference fringes. In Fig. 4(e)-(h) we show the calculated pattern 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 10[nm] regime and correspondingly a high atomic density in the focus may be obtained. Given 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 remaining 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.

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Note added in proof: Recently, a similar result has been reported \([21]\).