Measuring the Temporal Coherence of an Atom Laser Beam

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We report on the measurement of the temporal coherence of an atom laser beam extracted from a ^{87}Rb Bose-Einstein condensate. Reflecting the beam from a potential barrier creates a standing matter wave structure. From the contrast of this interference pattern, observed by magnetic resonance imaging, we have deduced an energy width of the atom laser beam which is Fourier limited by the duration of output coupling. This gives an upper limit for temporal phase fluctuations in the Bose-Einstein condensate.

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One of the fundamental properties characterizing a matter wave source is its degree of temporal coherence. Perfect coherence in the time domain would allow one to completely predict the phase evolution of the underlying field. In light optics, a laser comes closest to this ideal situation. The temporal coherence of a laser exceeds that of a thermal light source by far, which is central to many applications in spectroscopy, metrology, and interferometry. Similarly, a matter wave source based on Bose-Einstein condensation [1,2] is expected to have a substantially higher degree of temporal coherence than a thermal atom source. So far, experimental investigations of the coherence of Bose-Einstein condensates have focused on the spatial domain: The interference of two condensates has been observed [3], the uniformity of the spatial phase has been demonstrated [4,5], and the spatial correlation function has been determined [6].

A measurement of the temporal coherence of Bose-Einstein condensates or atom laser beams has not yet been reported. However, there are prospects to realize matter wave sources with coherence times comparable to state-of-the-art optical lasers. Theoretically, the energy width of a matter wave beam extracted from a Bose-Einstein condensate should approach the Fourier limit which is determined by the duration of the output coupling process [7]. Temporal fluctuations of the phase of a Bose-Einstein condensate are passed on to an atom laser beam that is coherently extracted from the condensate and will therefore ultimately limit the coherence properties of such beams. Phase diffusion at finite temperature [8] and fluctuations in the atom number [9] are expected to limit the coherence time of a Bose-Einstein condensate. The temporal evolution of the relative phase between two spin components of a Bose-Einstein condensate has been studied [10]. This measurement has shown the robustness of the relative phase, but it was insensitive to temporal phase fluctuations common to both components of the condensate.

We investigate the coherence time of an atom laser beam by measuring the contrast of the standing wave pattern that emerges when the atom laser beam is retroreflected from a potential barrier (Fig. 1). This interference process is different from atom optical interference experiments performed so far, where an atomic wave packet is coherently split and subsequently recombined [11]. In contrast, we study the interference of the reflected front end of the wave packet with its own back end. The measurement is therefore sensitive to phase fluctuations of the condensate in the time domain. The atom source and the detection scheme are independent from each other and common fluctuations are minimal. The reflecting barrier is formed by a linear magnetic potential several times steeper than the gravitational potential. The spatial structure of the standing matter wave cannot be resolved optically since it is about $1/5$ of the ^{87}Rb resonance wavelength. We have therefore developed a one-dimensional magnetic resonance imaging method which is based on rf spectroscopy between different atomic Zeeman sublevels.

The incoming atom laser beam is prepared in the $|m_F = 1\rangle$ Zeeman sublevel of the $F = 2$ hyperfine ground state and reflected by a magnetic field gradient of $B' = 200\frac{G}{cm}$. In this linear potential the stationary solutions of the Schrödinger equation are Airy functions $\mathrm{Ai}(\frac{z-z_0}{l})$, where z_0 is the apex of the classical trajectory [12]. The scaling parameter $l = (\frac{\hbar^2}{2m|\frac{dV}{dz}|})^{1/3}$ is determined by the potential gradient $\frac{dV}{dz}$ and the mass m of the atom. It has the value $l_{|m_F=1\rangle} = 170$ nm for the magnetic field gradient B' and the atomic state $|m_F = 1\rangle$, which has the magnetic moment $\mu = \mu_B/2$.

An rf field couples the atoms in the created standing matter wave to the $|m_F = 2\rangle$ Zeeman sublevel which has twice the magnetic moment. In that state the atoms experience approximately twice the potential gradient, and

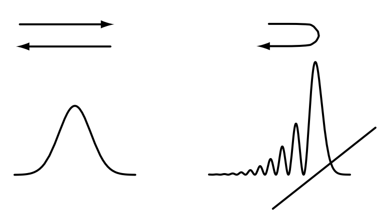

FIG. 1. Principle of the measurement. A wave packet reflected from a potential barrier develops a standing wave structure at the turning point.

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the scaling parameter $l_{|m_F=2\rangle}$ of the Airy function is correspondingly smaller (Fig. 2a). The transition probability p between the two states is proportional to the overlap integral of the Airy functions

$$p \propto \left| \int dz\, \mathrm{Ai}^{*}\!\left(\frac{z - z_{0,|m_F=2\rangle}}{l_{|m_F=2\rangle}}\right) \mathrm{Ai}\!\left(\frac{z - z_{0,|m_F=1\rangle}}{l_{|m_F=1\rangle}}\right) \right|^2 . \tag{1}$$

The contribution to the integral is significant only where the two functions have similar periodicity. This is predominantly the case in the vicinity of the turning points. The turning point of the $|m_F = 1\rangle$ atoms is fixed by the total energy of the incoming wave packet. The energy of the $|m_F = 2\rangle$ atoms, and hence their turning point, is set by the rf frequency. A variation in the rf frequency changes the transition probability p since the turning point of the atoms in the $|m_F = 2\rangle$ state is shifted with respect to the turning point of the atoms in the $|m_F = 1\rangle$ state. State selective analysis of the atom laser beam after the reflection allows us to measure the transition probability p in the experiment.

A Bose-Einstein condensate of 5×10^5 ^{87}Rb atoms is created in a QUIC trap [13] (a type of magnetic trap that incorporates the quadrupole and Ioffe configuration) by evaporative cooling in the $|F = 1, M_F = -1\rangle$ state. The atom laser beam is extracted from the condensate using cw output coupling [14]. A weak, monochromatic rf field transfers trapped atoms into the $|F = 1, m_F = 0\rangle$ state where they are accelerated by gravity and propagate downwards. A collimated beam is formed since the gravitational force largely exceeds the force that the atom laser beam experiences by the remaining condensate. After a dropping distance of 400 μm the atoms enter a region of two focused laser beams which transfer all atoms into the $|F = 2, m_F = 1\rangle$ state by a two-photon Raman transition. The resonance condition for this transition is given by the difference frequency between the two lasers and the local magnetic field [15]. In the low field seeking state $|F = 2, m_F = 1\rangle$ the atoms experience the increasing potential of the magnetic trapping field from which the atom laser beam is reflected. Sufficiently far away from the trap center this potential is given by $V(z) = (\mu B' - mg)z$ [13], where g is the gravitational acceleration along the vertical z axis.

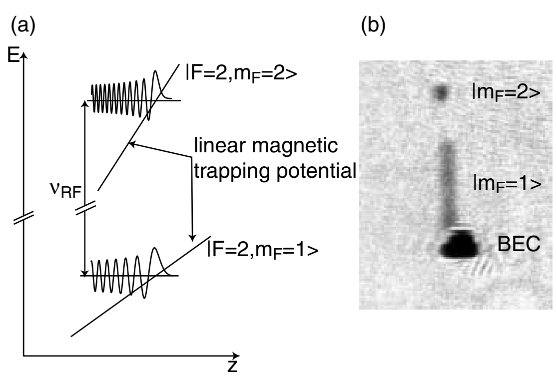

FIG. 2. (a) Schematic description of the rf spectroscopy. The atom laser approaches the potential barrier in the $|F = 2, m_F = 1\rangle$ state. The incident and the retroreflected wave form a standing wave pattern. This wave function is coupled to the $|F = 2, m_F = 2\rangle$ state by a radio frequency field. The wave function for atoms in the $|F = 2, m_F = 2\rangle$ has different periodicity and the overlap can be changed by shifting the turning points with respect to each other. (b) Longitudinal Stern-Gerlach separation in the inhomogeneous magnetic trapping field.

Approaching the turning point of their trajectory the atoms are exposed to the σ^+-polarized rf field which couples the $|F = 2, m_F = 1\rangle$ state to the $|F = 2, m_F = 2\rangle$ state. The fraction of atoms transferred to this state is determined in the following way. Because of the larger magnetic moment, atoms in the $|F = 2, m_F = 2\rangle$ state oscillate faster in the magnetic trap and spatially separate from atoms in the $|F = 2, m_F = 1\rangle$ state. After half an oscillation period the atoms in the $|m_F = 2\rangle$ state pile up in the upper turning point of their trajectory. At this instant the magnetic trapping field is switched off and an absorption image is taken from which the peak absorption of atoms in both states is determined (Fig. 2b).

In Fig. 3 rf spectra of standing matter wave pattern are displayed which are taken for atom laser beams of variable duration. The detected interference pattern directly shows the temporal phase coherence of the wave packet created by the atom laser. The observed contrast increases for increasing duration of the output coupling process. We compared each data set to a numerical calculation in which the overlap integral of Eq. (1) is calculated for Airy functions within a given energy width. We find good agreement with the experimental data when the energy widths for the calculations are chosen to be the convolution of the Fourier limit of the output coupling duration and the detector resolution of 1.8 kHz. The various contributions to the detector resolution are discussed in detail further below.

For an output coupling period of 1.5 ms we obtain an atom laser linewidth of (700^{+400}_{-250}) Hz, which is an upper limit for the temporal phase fluctuations of the Bose-Einstein condensate. The error is obtained from an estimated uncertainty of 10% in the convoluted energy width. The energy width of the atom laser beam is smaller than the 2 kHz mean-field energy of the condensate and much smaller than the energy span over which output coupling from the Bose condensate can be achieved, which, due to gravity, is about 15 kHz [14]. Furthermore, we see no evidence that impurity scattering events [16] hinder the superfluid flow [17] in the output coupling process. Those events would also cause a halo around the atom laser output, which we do not observe.

The 1.8 ± 0.3 kHz energy resolution of our experiment, which corresponds to a spatial resolution of 65 nm, can be attributed to technical fluctuations and geometrical contributions.

First, there are time-dependent variations of the field strength and position of the magnetic trap. Short-time

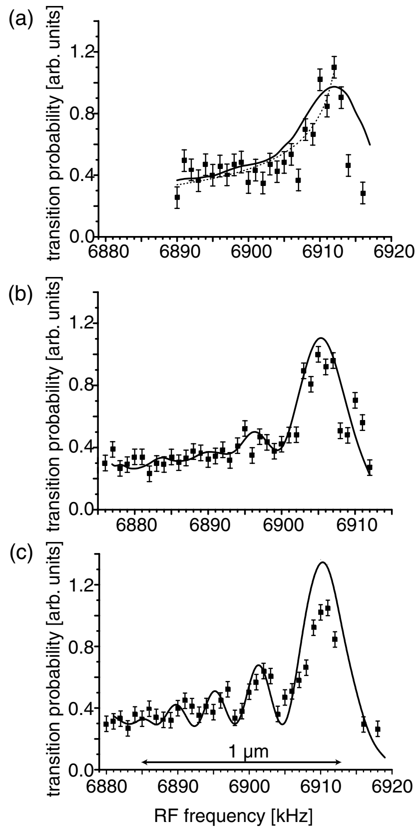

FIG. 3. The rf spectra for different output coupling durations. The overlap integrals (solid lines) are calculated for an energy width corresponding to the quadratic sum of the Fourier limited linewidth and the detector resolution of 1.8 kHz. They are scaled in amplitude to match the experimental data, but contain no free parameters. (a) A 200 μs atom laser beam. The dotted line is a fit $\propto 1/\sqrt{z - z_0}$ corresponding to the classical transition probability. (b) A 410 μs atom laser beam. (c) A 1.5 ms atom laser beam. The modulation of the transition probability in (b) and (c) is a signature of the quantum mechanical character of the reflection process. The individual data points of the rf spectroscopy have been taken in different repetitions of the experiment. The error bars are determined from repetitive measurements at a single frequency. They are largest for (a) due to the small atom number in the atom laser beam. The deviation of the data points from the main peak in (c) is due to saturation of the rf transition, the slight mismatch in oscillation frequency is due to fluctuations in the rf resonance condition, which are discussed in the text. A length scale is given in (c).

fluctuations (5–100 ms) of the magnetic field were minimized by employing a low noise power supply ($\Delta I_{\rm rms}/I < 10^{-4}$) and by placing the trap inside a magnetic shield enclosure. The motion of the magnetic trapping coils was passively decoupled from acoustic noise on the optical table by rubber sockets and the air-conditioning in the laboratory was switched off 10 s before the atom laser beam was extracted from the condensate. Using a seismic sensor we monitored the vibrations of the magnetic trap. All described time-dependent fluctuations amount to 700 Hz. Second, shot-to-shot variations of the resonance condition for the two-photon Raman transition modify the energy with which the atom laser beam approaches the magnetic field gradient barrier. The resonance condition is determined by the local magnetic field, the frequency difference between the Raman lasers, and their intensity. The shot-to-shot reproducibility of the current supply producing the magnetic field was measured to be better than 6×10^{-5} corresponding to 300 Hz. The difference frequency between the Raman lasers was stabilized to better than 10 Hz. Intensity fluctuations of the Raman laser beams change the light shift for the two atomic states, but only the difference in light shift changes the resonance condition. Being detuned $\Delta = 70$ GHz from the D_1 line we obtain for our experimental parameters a difference in light shift of 80 kHz/mW, which we have confirmed experimentally. The intensity of the Raman lasers is actively stabilized to a relative stability of 3×10^{-3} and the detuning was controlled to ± 15 MHz by adjusting current and temperature of the extended cavity diode lasers. Position noise of the Raman lasers with respect to the magnetic trapping field also changes the intensity of the Raman laser light at the location of the resonance. We minimize this effect by localizing the spin-flip resonance at the center of the Raman beams and position stabilizing the Raman laser focus with respect to the magnetic trapping coils. The remaining position jitter of 1/25 of the beam waist results in relative intensity fluctuations of 3×10^{-3} at the center of the focus. The total contribution of technical noise to the energy resolution is 850 Hz.

The three-dimensional geometry of the magnetic field also limits the energy resolution obtained with the rf spectroscopy. Away from the center of an elongated Ioffe trap there is a weak axial magnetic field gradient, transverse to the atom laser beam. Therefore atoms on one side of the beam are reflected at a slightly different height compared to atoms on the other side. For a diameter of the atom laser of 70 μm this amounts to 2 kHz energy difference across the beam. By evaluating the optical density in the absorption images only in the center of the reflected wave packets we can reduce this effect by a factor of 4. The resonance condition for the rf spectroscopy is given by the surface of constant magnetic field strength. In the radial plane this resonance shell is misaligned with respect to the surfaces of constant energy of the reflection barrier. This misalignment is due to gravity and amounts to 1.5 kHz across the beamwidth.

From an atom optical point of view the magnetic trapping potential is a matter wave cavity for the atoms in the $|F = 2, m_F = 1\rangle$ state. The observed interference fringes unambiguously show the spatial structure of the modes in this cavity. The formation of a standing wave pattern demonstrates that the cavity "mirrors" [15] preserve the coherence of the incident atoms. The longitudinal mode spacing of the cavity for our parameters is $\Delta\omega = 2\pi \times 63$ Hz which means that we populate about 10 modes in the experiment, depending on the output coupling duration. This is an improvement of 3 orders of magnitude over previous experiments with laser cooled atoms, where the number of populated modes is determined by the size and temperature of the cold atom source. With a further enhancement of the energy resolution in our experiment it should be possible to manipulate individual modes in a matter wave cavity. An alternative experiment for the observation of a standing matter wave in a linear potential is proposed for ultracold neutrons [18].

The experimental resolution of the rf spectroscopy may be improved by focusing the atom laser beam onto the reflecting magnetic field gradient. The geometrical energy width scales approximately linearly with the beam diameter, so focusing by a factor of 100 will greatly improve the resolution. It seems feasible to achieve a resolution of 10 Hz by reducing the light shift fluctuations and enhancing the magnetic field stability when operating the coils from a battery. In this regime a transition to a Lorentzian line shape of the atom laser is expected, when the output coupling rate (which is much smaller than the trapping frequencies $\Gamma \simeq 10\ \mathrm{s}^{-1} \ll \omega = 2\pi \times 100$ Hz) dominates compared to the output coupling duration [7]. For a reduced output coupling rate a decrease of the coherence time due to number fluctuations in the condensate, which is expected to be on the order of 10 Hz [9], might become visible. Analogous to the Schawlow-Townes limit for optical lasers [19], phase diffusion processes [8] will ultimately limit the linewidth of an atom laser to a few Hz.

In conclusion, we have measured the temporal coherence of an atom laser beam. A standing matter wave is created by retroreflecting the atom laser beam from a potential barrier. Employing magnetic resonance imaging we detect the interference structure with a spatial resolution of 65 nm. For the atom laser beam we deduce a Fourier limited energy width of 700 Hz, which is substantially below the mean-field energy of the Bose-Einstein condensate. Our results show that phase fluctuations in the condensate are negligible on the time scale of our measurement and that the output coupling process preserves the coherence of the atom laser.

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