Matter-wave Interferometry with Phase Fluctuating Bose-Einstein Condensates

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(Dated: February 1, 2008)

Elongated Bose-Einstein condensates (BECs) exhibit strong spatial phase fluctuations even well below the BEC transition temperature. We demonstrate that atom interferometers using such condensates are robust against phase fluctuations, i.e. the relative phase of the split condensate is reproducible despite axial phase fluctuations. However, larger phase fluctuations limit the coherence time, especially in the presence of some asymmetries in the two wells of the interferometer.

PACS numbers: 03.75.Dg, 39.20.+q, 03.75.-b, 03.75.Lm

A non-interacting zero temperature Bose-Einstein condensate is the matter-wave analogue to the optical laser, and therefore the ideal atom source for atom interferometry. Finite temperature and atomic interactions profoundly change the coherence properties of a condensate and introduce phase fluctuations and phase diffusion. Those phenomena are of fundamental interest, but also of practical importance because they may limit the performance of atom interferometers. This applies in particular to magnetic microtraps and waveguides (e.g. atom chips) since tight confinement and elongated geometry enhances phase diffusion and phase fluctuations.

Phase diffusion is a quantum effect associated with the coherent splitting of the condensate. Number fluctuations lead to density fluctuations, which, due to interactions, cause fluctuations of the energy and cause diffusion of the relative phase proportional to the chemical potential times the relative atom number. In our previous work, we showed that such phase diffusion could be dramatically reduced by number squeezing, increasing the coherence time. In this paper, we characterize and discuss the role of spatial phase fluctuations in an atom interferometer.

Phase fluctuations cause the condensate to break up into several quasi-condensates with random phase, i.e. long range coherence is lost. This usually happens in elongated geometries when the temperature is sufficiently high to excite such modes, or in interacting one-dimensional condensates even at zero temperature due to quantum fluctuations. Spatial phase fluctuations have two major consequences for atom interferometry. First, they speed up phase diffusion, since the chemical potential, , the amount of fluctuations in the relative atom number. In our previous work, we showed that such phase diffusion could be dramatically reduced by number squeezing, increasing the coherence time. In this paper, we characterize and discuss the role of spatial phase fluctuations in an atom interferometer.

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FIG. 1: (Color online) Geometry of the atom chip interferometer. (a) Atoms were confined radially by the combined magnetic potential of a current-carrying wire and an external bias field. A pair of endcap wires (not shown) provided axial confinement. The single well was deformed into a vertical double well within 15 ms by adding rf current into the trapping wire dressing the atoms with oscillating rf fields. Absorption image was taken by a probe beam directed along the condensate axis [(b), axial imaging] and perpendicular to the condensate axis [(c), side imaging]. All data in this paper were obtained using side imaging. The fields of view are 160 × 260 µm and 180 × 100 µm for axial and side imaging respectively.

The longitudinal phase fluctuations were quantified by measuring the root-mean-square average of the density fluctuations as described in Fig. 2 [16]. The amount of phase fluctuations was controlled by changing the atom number and the temperature with rf-evaporation. The rf field generated by the rf wire [Fig. 1(a)] was swept down from ~ 10 kHz above the Larmor frequency at the trap center to a variable final value, leading to a variable chemical potential and temperature of the condensate (Fig. 2 inset). The variation of the spatial phase fluctuations with chemical potential is shown in Fig. 2.

Having firmly established the presence of phase fluctuations, we can now demonstrate the robustness of an atom interferometer against longitudinal phase fluctuations. For this, we split the condensates and observe the reproducibility of interference fringes obtained by recombining the condensates during ballistic expansion. The regular, almost straight interference fringes (Figs. 1 and 3) show that the spatial phase fluctuations are common mode and don’t affect the relative phase in a major way. However, when we increase the amount of phase fluctuations, we observe an increasing blurring or waviness of the interference fringes (Fig. 3). The number of wiggles of the waviness is comparable to the modulation pattern observed in the ballistic expansion of single condensates (Fig. 2). For the smallest amount of spatial phase fluctuations, the relative phase is almost constant along the
FIG. 3: (Color online) Effect of spatial phase fluctuation on the waviness of interference fringes. (a) Interference fringes obtained right after splitting a condensate. For large spatial phase fluctuation (e.g. 4.6 kHz), the fringe pattern shows more significant wiggles than for smaller phase fluctuations (e.g. 3.6 kHz). (b,c) From the fringes for 3.6 kHz (dashed line) and 4.6 kHz (solid line) chemical potentials, relative phases are obtained along the axial direction. In both cases, the overall relative phase can be well-determined by averaging along the axial coordinate, but considerable axial variations of the relative phase were observed in the regime of large longitudinal phase fluctuations (solid line).

To quantify the reproducibility of the relative phase, we determine the probability of random phase (called randomness) \[ \mu \] (Fig. 4). For values of the chemical potential larger than 3.0 kHz, the randomness is less than 0.1 which implies a reproducible phase with 90% confidence. However, by comparing Figs. 2 and 4, one clearly recognizes the degradation of reproducibility of the relative phase with increasing spatial phase fluctuations.

By introducing a variable hold time after the splitting, we can examine how spatial phase fluctuations limit the coherence time of a matter-wave interferometer. Fig. 5 shows the increase of randomness with hold time. For the smallest amount of phase fluctuations (chemical potential \( \sim 3.4 \) kHz, black squares in Fig. 5), the phase coherence time is \( \sim 23 \) ms. As the spatial phase fluctuations increase (solid circles and open squares in Fig. 5), the phase coherence time becomes shorter. It should be noted that in the absence of spatial phase fluctuations, for a condensate with zero temperature, the rate of phase diffusion decreases with chemical potential, proportional to \( \sim \mu^{-1/4} \) [3, 4], which is also valid at finite temperature [8]. Our observed increase of decoherence with increasing chemical potential is therefore attributed to the increase of spatial phase fluctuations. The increasing waviness of the interference fringes show that the decoherence is caused by randomization of the relative phase along the axial direction [Fig. 5(b)].

By which mechanism do the spatial phase fluctuations affect the interferometer signal? For our experimental parameters, the rate of phase diffusion (assuming Poissonian number fluctuations after the splitting) is \( \sim 20 \) ms [3, 4]. For our value of \( T/T^* \), the condensate fragments into \( \sim 10 \) quasicondensates which should decrease the coherence time by a factor of \( \sqrt{10} \) to about 7 ms. Our observation of much longer coherence times implies strong squeezing of the relative number fluctuations, as already observed in Ref. [11]. In Ref. [11] we inferred a reduction of the number fluctuations below shot noise by a factor of ten. However, having now established the presence of strong phase fluctuations, we should reinterpret our previous result. Those data were taken at a value of \( T/T^* \) of about 7, which implies that the number fluctuations for each quasi-condensate was squeezed.

FIG. 4: Effect of spatial phase fluctuations on the reproducibility of the relative phase right after splitting. The probability of random phases was measured with variable longitudinal phase fluctuations immediately after splitting (0 ms hold time).
by a factor of \( \sim 25 \). Our current experiments were carried out in a rotated geometry (in order to be able to observe along a radial direction), but the value of \( T/T^* \sim 10 \) is similar. If we assume that the squeezing factor is the same, then we should have observed phase coherence times comparable to the 200 ms observed previously \([11]\).

We therefore conclude that the shorter coherence times observed in this paper are not limited by the fundamental quantum phase diffusion of quasi-condensates because of strong number squeezing, but rather reflect the interplay of spatial phase fluctuations and some random relative motion of the two condensates after splitting. This is probably due to some asymmetries in the current trapping potential \([17]\). The loss of coherence due to phase fluctuations starts already during the splitting process (Figs. 3 and 4), and increases with hold time.

The main conclusions of this paper are that matter wave interferometers are robust against spatial phase fluctuations, especially when strong number squeezing mitigates the fragmentation into smaller quasi-condensates (which show faster phase diffusion than a single condensate). However, spatial phase fluctuations make the interferometer much more sensitive to residual relative motion of the two split condensates and therefore require a highly symmetric double well potential.

This work was funded by DARPA, NSF, and ONR. G.-B. Jo and Y.-R. Lee acknowledge additional support from the Samsung foundation. We thank H. Kim for experimental assistance and Y. Shin for critical reading of the manuscript. We also thank E. Demler for stimulating discussions.
In our trap geometry, the two condensates in vertically separated potential wells feel different magnetic fields from a pair of endcap wires. The slightly asymmetric axial confinement leads to some quadrupolar relative motion of the two separated condensates. For the determination of the relative phase, we select the central region where the fringes were parallel to the axial direction.