Measuring Relative Atom Number Fluctuations in a Coherently Split Bose Einstein Condensate

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Abstract: We report direct measurements of number fluctuations between two BECs. A single BEC is dynamically and coherently split in two. Fluctuations in the relative atom number in repeated trials are evaluated against binomial random fluctuations.

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1. Introduction

A major motivation for reducing the atom number fluctuations in an atomic "beam splitter" is the potential application to atom interferometers with confined atoms. Bose-Einstein condensates (BECs) confined to two waveguides are an attractive system due the inherent phase coherence of the condensate and the long interrogation times afforded by confinement. One problem with this system - phase diffusion - is mitigated when number fluctuations are suppressed. Sub-shot-noise number fluctuations have been indirectly observed after splitting a single BEC into two confined halves, releasing the two BECs and measuring the phase coherence of the splitting process from the resulting matter wave interference pattern [1, 2]. We have established a method to measure atom number fluctuations directly with a precision 1%. We use this method measure the atom numbers in the left (L) and right (R) wells after splitting, and thus the fluctuations in the relative atom number $N_r = N_R - N_L$ in successive repetitions of the experiment.

2. Josephson junction model and predictions

A simple treatment of the splitting problem in terms of a cloud of N_T classical particles divided evenly and randomly into two clouds yields the familiar "root-N" result: the expected standard deviation in N_r is equal to $\sqrt{N_T}$. This result, derived using binomial statistics and assuming that each atom has equal probability of ending up in the left or right cloud, is often referred to as the shot-noise limit. Sub-shot-noise fluctuations in N_r in the interacting BEC system are predicted by a model which describes the splitting process using a Josephson Hamiltonian with time-dependent barrier height and tunnelling [3, 4]. In this "two-mode" model one considers only the two lowest-energy eigenstates of the double-well potential, namely the symmetric and anti-symmetric ground states. It is further assumed that the splitting is carried out slowly enough ("adiabatically") so that the BEC population is transferred from the single-well ground state into the double-well ground state without populating higher-energy double-well eigenstates.

In the Josephson oscillator picture the Hamiltonian may be written $H \approx (E_C/2)N_r^2 + (E_J/2)\theta_r^2$ for small values of the relative phase. N_r and θ_r are the relative atom number and relative phase, and E_C and E_J the charging and tunnelling energies. As the barrier is raised and the tunnelling energy E_J decreases, the Josephson plasma frequency $\hbar\omega_J = \sqrt{E_C E_J}$ decreases exponentially in time with time-constant τ. The width of the ground state wavefunction in the number representation may then be written $\Delta N_r \approx \sqrt{5\hbar N_T/4\mu\tau}$, where N_T is the total atom number ($N_R + N_L$) and μ the chemical potential. To obtain this expression for ΔN we have assumed that BEC is evenly split into two halves so that $\mu_L = \mu_R = \mu$ and $N_L = N_T/2$, and have used the Thomas-Fermi limit expression $E_C = 4\mu_L/5N_L = 8\mu/5N_T$ [5]. With appropriate choices for μ and τ this formula predicts sub-shot-noise fluctuations: $\Delta N_r < \sqrt{N_T}$, hence the label "number squeezing" [1, 2, 5].

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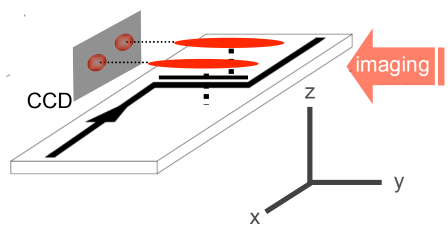
3. Method: adiabatic double-well potentials

We create a single BEC of $N \sim 10^4$ ^{87}Rb atoms with $T_C \sim 300$ nK in an elongated 3-dimensional harmonic magnetic trap using an atom chip [6]. The trap is then dynamically deformed into a double-well potential by applying a time-varying radio-frequency (RF) magnetic field to the trapped atoms, and sweeping the RF frequency from below to above resonance with the magnetic hyperfine energy levels of the atoms [7]. The barrier height and well separation of the double-well are controlled by the RF frequency and amplitude. The final RF frequency and amplitude are chosen so that the barrier height exceeds the chemical potential at the end of the frequency sweep. At this point, left-right tunnelling has ceased and the left and right well populations are fixed, but the double-well separation, typically on the order of 2 - 5 μm, is too small to resolve optically and measure relative atom number. We therefore perform a second, more rapid sweep of the RF frequency, which increases the double-well separation until the left and right clouds are well resolved. This final separation is typically on the order of 150 μm.

Once the separation RF ramp is complete, we turn off all magnetic trapping fields and perform resonant absorption imaging after 2 ms of time-of-flight expansion. We image along the axial (longitudinal) direction of the two split condensates, as shown in Figure 1. The axially-integrated absorption spots are analyzed and used to compute the atom number in each of the two clouds.



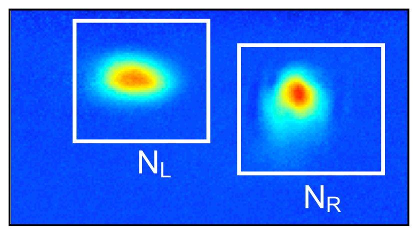


Figure 1: (left) Imaging geometry of the two split BECs. The BEC is split along the *x* direction. Absorption imaging is carried out along the longitudinal *y* direction. **(right)** Example absorption image of two split BECs collected after splitting, separation, and 2 ms time-of-flight. The cloud separation in this image is 160 μm.

From the absorption image we compute N_R, N_L and N_r. To build up statistics of the relative atom number we repeat the above preparation, splitting and measurement steps. A typical data set consists of 100 to 200 separate realizations of the split BEC. The variance of the shot-to-shot fluctuation of N_r is computed and compared to the "root-N" shot-noise fluctuation level. Thus far we have observed fluctuations in N_r at the shot noise limit.

4. Research questions

We are most interested in evaluating predictions and assumptions of the two-mode Josephson model of splitting. In particular: (a) the role of finite temperatures and thermalization and their consequences for the two-mode assumption; (b) the connections between the adiabaticity condition, relative number fluctuations and the speed with which the barrier is raised and the double-well created. Finally, we also are interested in extending this work to split fermionic systems.

5. References

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