Extended Coherence Time with Atom-Number Squeezed Sources

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Coherence properties of Bose-Einstein condensates offer the potential for improved interferometric phase contrast. However, decoherence effects due to the mean-field interaction shorten the coherence time, thus limiting potential sensitivity. In this work, we demonstrate increased coherence times with number squeezed states in an optical lattice using the decay of Bloch oscillations to probe the coherence time. We extend coherence times by a factor of 2 over those expected with coherent state BEC interferometry. We observe quantitative agreement with theory both for the degree of initial number squeezing as well as for prolonged coherence times.

Experimental requirements for precision atom interferometry are well suited to many of the coherence properties of Bose-Einstein condensates [1, 2, 3, 4, 5]. BECs possess narrower momentum distributions than those of ultra-cold atomic gases, which removes the need for velocity selection during initial state preparation. The longer coherence length of a condensate improves phase contrast, and colder temperatures reduce ensemble expansion during long interferometer interrogation times. Furthermore, for confined atom-interferometers [4, 6, 7] which require spatial separation of a wavepacket in close proximity to a guiding surface, the superfluid properties of a BEC offer an additional advantage. The mean-field interaction energy in BECs provides an energy gap to external excitations, effectively decoupling the atomic proof-mass from the physical sensor.

On the other hand, the coherence time for BEC interferometry can be significantly reduced with respect to cold atom sources. Prior to separation, two linked condensates have relative number fluctuations which support a well defined relative phase. However, when separated, the interplay of a large on-site mean-field interaction with large number variance causes rapid dephasing [3]. This concern has been addressed previously by using either dilute condensates [10] or alternatively, Fermi gases which do not suffer from density broadening mechanisms [11]. It is possible, however, to retain some of the benefits of BEC interferometry while minimizing mean-field induced decoherence. The generation of atom-number squeezed states from a BEC in an optical lattice [12, 13] has offered the possibility to create states with reduced sensitivity to mean-field decay mechanisms.

In this work, we study the characteristic time scale for which an array of BECs preserves relative phase information after becoming fragmented, and we observe prolonged coherence times for number squeezed states. The coherence time is probed through the decay time of a Bloch oscillation, and we find quantitative agreement with theoretical predictions.

The theoretical treatment for a BEC in an optical lattice begins with the Bose-Hubbard Hamiltonian [14],

\[ H = -\gamma \sum_i (\hat{a}^\dagger_{i+1} \hat{a}_i + H.c.) + \sum_i \varepsilon_i \hat{N}_i + \frac{g\beta}{2} \sum_i \hat{a}^\dagger_i \hat{a}^\dagger_i \hat{a}_i \hat{a}_i (1) \]

where \( g \beta \) represents the mean-field interaction energy and \( \gamma \) is the inter-well tunneling matrix element with both terms dependent on lattice depth. \( \varepsilon_i \) denotes the external potential term and \( \hat{a}_i \) and \( \hat{a}_i^\dagger \) represent single particle annihilation and creation operators respectively at the \( i \)th lattice site. \( \hat{N}_i \) denotes local atom number which is replaced by the central well occupation \( N \) in the discussion below.

In the regime of low lattice potential and correspondingly large tunneling \( (N\gamma \gg g\beta) \) the many-body ground state of the system is described by a superfluid state with local atom number uncertainty \( \sigma(N) = \sqrt{N} \). As the potential barrier is adiabatically raised, the interplay of the interaction and tunneling terms renders number fluctuations energetically unfavorable. In the Bogoliubov limit, number fluctuations decrease with increasing lattice potential as \( \sigma(N) = (\frac{N^2}{1 + N\beta/\gamma})^{1/2} \), with commensurately increasing on-site phase fluctuations. In the limit of \( N\gamma \ll g\beta \), the system enters the Mott-Insulating regime, where the wavefunction at each site approximates an atom-number Fock state [13].

We fragment this array by frustrating tunneling between adjacent lattice sites. In previous work, this has been achieved by diabatically raising a large potential barrier [12, 16]. In this work, we frustrate tunneling by applying a large energy gradient across the array. This method is preferred since the on-site mean field energy (the third term on the right of Eq. 1) is unaffected by this process. This sudden localization is analogous to a beam splitter which instantly separates an ensemble into two distinct paths. The many-body ground state does not have time to react to the perturbation, and therefore an array of independent, localized many-atom states is formed. The initial array state is no longer in the ground state, and therefore, the array phase collapses.

Relative phase dispersion between adjacent wells is intuitively understood by considering an array initially prepared in a shallow lattice potential. After fragmentation,
The frequency of Josephson tunneling, which is valid for
turning on the optical lattice [22]. Finally, we measure
sure the period of Kapitza-Dirac diffraction by suddenly
citation from the lowest energy band [21]. We also mea-
first measure
and $k$
$\Upsilon$
$\mu$
$\gamma$
$\sigma_{\alpha}(N)$
$\tau_\alpha = (g\beta(\frac{N^2}{1+Ng\beta/\gamma})^2)^{-1}$.

We measure $\tau_\alpha$ for different initial number variances
by studying the decay of coherent Bloch oscillations [17, 18, 19]. An energy gradient $\epsilon_i = Ei$ is applied to the
array where $E$ is written in units of energy. This drives
an oscillatory response in the quasimomentum, $q$, of the
atomic Bloch state with a period $T = h/2\pi E$. Although
Bloch oscillations are traditionally observed for conditions
where the array is described by bands delocalized spatially
over many lattice sites, they also occur for spatially
localized wavefunctions described in the Wannier-
Stark basis [20]. We isolate the lattice sites when $E \gg \gamma$
but ensure that $E$ is not too large as to cause particle
loss through Zener tunneling [2]. The Bloch oscillation is
observed experimentally by interferometrically following
the evolution of the relative phase between adjacent wells
$\Delta \Phi = q\lambda/2h$, where $\lambda/2$ is the lattice period. Dispersion
in momentum space provides a quantitative indication of
dephasing.

The apparatus used in this experiment has been de-
scribed in detail [12]. We load $10^8$ $^{87}$Rb atoms into a
time-orbiting potential (TOP) trap. Evaporative cooling
generates a BEC in the $|F = 2, m_F = 2\rangle$ state with 1500
atoms, density $\rho \sim 10^{12}$ cm$^{-3}$ and temperature $\sim 0.2
T_c$. Atom number is determined with absorptive imag-
ing with 20% shot-to-shot fluctuations and is consistent with
the observed condensate fraction as a function of temperature.

We trap the condensate in a 1-D, vertically oriented
optical lattice. The lattice light is red detuned from the
$^{87}$Rb resonance and has $1/e$ radii of 60 $\mu m$. The poten-
tial depth, $U$, (measured in $E_R$, where $E_R = \hbar^2k^2/2m$
and $k = 2\pi/\lambda$ with $\lambda = 852$ nm) is calibrated using three
independent methods which all agree to within 10%. We
first measure $U$ by driving an even parity parametric ex-
citation from the lowest energy band [21]. We also mea-
sure the period of Kapitza-Dirac diffraction by suddenly
turning on the optical lattice [22]. Finally, we measure
the frequency of Josephson tunneling, which is valid for
low lattice depths, $U < 12 E_R$ [23]. For lattice depths
explored in this work ($5 < U < 24 E_R$) we calculate
$2\pi \times 4 < \gamma/h < 2\pi \times 250$ Hz, $2\pi \times 0.6 < g\beta/h < 2\pi \times 1.8$
Hz and $103 < N < 150$, and the vertical $1/e$ condensate
array radius ranges between 7 – 10 lattice sites.

After state preparation in the optical lattice (Fig. 1A),
we drive a Bloch oscillation by applying a magnetic field
gradient along the array axis. We probe the coherence
of the Bloch oscillation by releasing the array, rapidly
switching off the lattice within 500 ns. The interferomet-
ric signal is absorptively imaged with single atom detection
sensitivity. Fig. 1B shows images depicting a Bloch
oscillation with $T = 1.1$ ms, taken with $U = 10 E_R$
and $E/h = 2\pi \times 900$ Hz.

We ensure that adjacent sites are decoupled during
$T_{\text{Bloch}}$ by varying $E$ and measuring the width of the central interference peak. An increased width indicates
dephasing of the Bloch oscillation. We apply the field
gradient for 40 ms before releasing the array. We see in
Fig. 1C that for small $E$ the Bloch oscillation shows
minimal dephasing. However, for large energy offsets the
peak width increases, saturating at our resolution limit
for $\gamma \sim E$, where $\gamma/h = 2\pi \times 39$ Hz for $U = 12 E_R$.

We next quantify the degree of number squeezing gen-
erated at a given lattice depth. We adiabatically increase
the lattice intensity and then interfere the array, generating
an interference pattern with sharp peaks on top of a

![Figure 1](image-url)

**FIG. 1:**
A) Lattice intensity is shown for the experimental sequence. The lattice intensity is ramped up in $T_{\text{ramp}} = 350$ ms and then held constant for $T_{\text{Bloch}}$ during which time a magnetic field gradient is applied. The lattice and magnetic fields are turned off and the atoms ballistically expand for a 12 ms Time of Flight (TOF) before being imaged with a probe pulse. B) Absorptive images indicating a Bloch oscillation are shown. C) Peak width vs. energy offset $E$ is shown with widths con-
verted to units of $2\hbar k$. Insets show absorptive images both with and without dephasing.
We observe good correlation of $\tau_c$ with that expected for isolated coherent state condensates. For deeper lattice depths, however, we measure long coherence times which are in quantitative agreement with theoretical number squeezed state dephasing. For number squeezed states prepared at $U = 22.5\, E_R$, $\tau_c = 19.3\pm 3.5\, ms$. This represents an increase of a factor of 2.1 over the expected decay time of an array of coherent states in the same lattice potential. It is interesting to note that here squeezing extends the coherence time; typically, the enhanced fragility of squeezed states to loss mechanisms results in reduced coherence times.

With demonstrated control over number squeezing and site localization, we explore the dependence of $\tau_c$ on initial number variance. Using the experimental sequence in Fig. 1A, we take an absorptive image of the interfering atoms for different lattice depths with $E$ kept constant. We fit the central vertical peak to a Gaussian to determine the width as a function of $T_{\text{Bloch}}$. We measure $\tau_c$ by fitting the data as in Fig. 2B to $w(t) = w_f - (w_f - w_0)e^{-(t/\tau_c)^2}$. $w_f$ is the maximum observed width representing a fully dephased signature, and $w_0$ is the peak width prior to any phase dispersion.

FIG. 3: A) Peak width vs. $\omega_{\text{RF}}/2\pi$. $T_c = 1.6\, MHz$ for a BEC in the bare harmonic trap. B) Peak width vs. $T_{\text{ramp}}$.

To eliminate other potential sources of dephasing, we investigate the effects of finite temperature and the adiabaticity of our lattice ramp on the interferometric peak width observed in Bloch oscillations. We prepare condensates at different temperatures by varying the final frequency $\omega_{\text{RF}}$ of the evaporative cooling stage. As seen
in Fig. 3A, we observe no change in peak width for \(2\pi \times 1.40 < \omega_{RF} < 2\pi \times 1.50\) MHz with \(U = 16\ E_R\). However, at \(\omega_{RF} = 2\pi \times 1.51\) MHz we observe a sudden onset of phase broadening. To avoid this thermal dephasing regime all data was taken with \(\omega_{RF} = 2\pi \times 1.44\) MHz. Note that this critical temperature in the lattice is different from the BEC transition temperature in a bare harmonic trap (corresponding to \(\omega_{RF} = 2\pi \times 1.6\) MHz).

In Fig. 3B, we investigate the dependence of peak width on lattice intensity ramp speed. A balance is required to avoid losses due to lattice heating with very long ramp times and non-adiabaticity effects with short ramp times. We find that peak width is insensitive to ramp speed for \(80 < T_{\text{ramp}} < 620\ \text{ms}\).

![Graph](image)

FIG. 4:
Peak width is plotted vs. continued hold time in lattice after removing the external field gradient, \(T_{\text{rephase}}\). Insets are absorptive images showing initial dephasing of the phase contrast and subsequent revival.

As a final consideration, we explore the possibility for coherence restoration after complete dephasing. We use the same experimental sequence as in Fig. 1A, with \(U = 10\ E_R\) and \(T_{\text{Bloch}} = 80\ \text{ms}\), ensuring that dephasing has occurred. This time, however, after turning off the magnetic field gradient we continue to hold the atoms in the optical potential before interfering them. We see phase contrast return nearly completely after a rephasing time \(\tau_r \sim 10\ \text{ms}\) as shown in Fig. 1B. While the details of this rephasing mechanism require further investigation, a two-well model predicts this time to be determined by the generalized Josephson frequency \(\omega_J = \sqrt{Ng\beta\gamma}\). Our observed rephasing time is in excellent agreement with this prediction for our parameters [24].

In conclusion, we have demonstrated that number squeezed states in an optical lattice can extend coherence times for interferometry. We have obtained quantitative agreement with theory both in calibrating the number variance of our initial state as well as in observed coherence times with number squeezed states. For sensitivity considerations in practical interferometers, however, note that extended coherence times come with the price of increased phase noise due to number squeezing. Future work will explore this tradeoff in optimizing absolute sensor performance.

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