Control of Interaction-Induced Dephasing of Bloch Oscillations

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We report on the control of interaction-induced dephasing of Bloch oscillations for an atomic Bose-Einstein condensate in an optical lattice. We quantify the dephasing in terms of the width of the quasimomentum distribution and measure its dependence on time for different interaction strengths which we control by means of a Feshbach resonance. For minimal interaction, the dephasing time is increased from a few to more than 20 thousand Bloch oscillation periods, allowing us to realize a BEC-based atom interferometer in the noninteracting limit.

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Ultracold atomic systems have initiated a revolution in the field of precision measurements. Laser cooled thermal samples are used for ultrahigh resolution laser spectroscopy [1], are at the heart of modern atomic fountain clocks [2,3], and allow for the realization of matter-wave interferometers for high-precision inertial sensing [4] and high-precision determination of fundamental constants [5]. Atomic Bose-Einstein condensates (BEC), the matter-wave analog to the laser, combine high brightness with narrow spatial and momentum spread. In general, the resolution is limited only by the quantum mechanical uncertainty principle, and BECs could thus serve as ideal sources for precision measurements and, in particular, for matter-wave interferometers [6]. Atom-atom interactions, however, have to be taken into account, as they lead to collisional dephasing and give rise to density dependent mean-field shifts in the interferometric signal. It is thus advisable to either operate a BEC-based atom interferometer in the dilute density limit, possibly sacrificing a high signal-to-noise ratio, or to find ways of reducing or even nulling the strength of the interaction altogether. Precisely the latter is feasible in the vicinity of magnetically induced Feshbach resonances where the atomic s-wave scattering length and hence the strength of the atom-atom contact interaction go through a zero crossing [7]. It is thus possible to experimentally investigate the reduction and even disappearance of interaction-induced effects on the interferometric signal as the scattering length is tuned towards zero by means of an externally controlled magnetic field.

A paradigm atom interferometric effect is the well-known phenomenon of Bloch oscillations [8]. Bloch oscillations for the mean quasimomentum are the result of single atom interference as the atomic wave packet, subject to a constant force, is Bragg reflected in the presence of a periodic optical lattice potential. They have been observed for ultracold thermal samples [5,8–10], for atoms in interacting BECs [11,12], and for ensembles of noninteracting quantum-degenerate fermions [12]. For the case of the interacting BEC, strong dephasing is found as evidenced by a rapid broadening and apparent smearing out of the momentum distribution in the first Brillouin zone, limiting the observation of Bloch oscillations to a few cycles for typical atomic densities in a BEC. In addition, the measured initial width of the momentum distribution is comparable to the extent of the Brillouin zone, as interaction energy is converted into kinetic energy upon release of the BEC from the lattice potential, thus greatly reducing the contrast of the oscillations [12].

In this Letter, we report on the control of interaction-induced dephasing of Bloch oscillations for a BEC in a vertically oriented optical lattice under the influence of gravity. Control is obtained by means of a zero -crossing for the atomic s-wave scattering length a. We observe the transition from an interacting BEC to a noninteracting BEC by measuring the rate of dephasing, given by the change of the width of the momentum distribution, as a function of a. We identify a clear minimum for the dephasing which we associate with the zero crossing for a. At the minimum, more than 2×10^4 oscillations can be observed with high contrast, and the zero crossing can be determined with high precision. For our measurements at nonzero scattering length, we greatly reduce broadening of the momentum distribution by rapidly switching the interaction strength to zero upon release from the lattice potential. Our measurements indicate that BECs can indeed be used as a source for precision atom interferometry, as effects of the interaction can be greatly reduced. For a noninteracting BEC, we intentionally induce dephasing by means of a weak optical force gradient and observe collapse and revivals of Bloch oscillations.

The starting point for our experiments is an essentially pure BEC with typically 1×10^5 Cs atoms in the $|F = 3, m_F = 3\rangle$ hyperfine ground state sublevel confined in a crossed-beam dipole trap generated by one vertically (L_1, with $1/e^2$-beam diameter 256 μm) and one more tightly focused horizontally (L_2, with diameter 84 μm) propagating laser beam at a wavelength near 1064 nm. We support the optical trapping by magnetic levitation against gravity [13]. For BEC preparation, we basically follow the procedure described in Refs. [13,14]. The strength of the interaction can be tuned by means of a broad Feshbach resonance with a pole at -11.7 G. The resonance causes a zero crossing for the scattering length a near an offset magnetic field value of 17 G with a slope of 61 $a0$/G [15]. Here, a_0 denotes Bohr's radius. The lattice potential is generated by a vertically oriented standing laser wave generated by retro-reflection, collinear with L_1, but with much larger diameter of 580 μm. This allows independent control of lattice depth and radial (i.e., horizontal) confinement. The light comes from a home-built single-mode fiber amplifier [16] seeded with highly-stable light at $\lambda = 1064.494\,6(1)$ nm. We turn on the optical lattice potential exponentially to a depth of $7.9E_R$ within 1000 ms, where $E_R = h^2/(2m\lambda^2) = k_B \times 64$ nK is the photon recoil energy and m is the mass of the Cs atom. The slow ramp assures that the BEC is adiabatically loaded into the lowest Bloch band of the lattice, and it avoids horizontal excitations. We load between 40 to 65 lattice sites, depending on the initial vertical extent of the BEC. We then reduce the power in L_2 to zero within 300 μs. Subsequently, the magnetic field gradient needed for levitation is ramped down, and a bias magnetic field is tuned to the desired value within 100 μs. For the present experiments, we adjust a in the range from -2 to 300 a_0 with magnetic bias fields from 17 to 23 G. The step in a leads to some unavoidable horizontal excitation as a result of the change of the Thomas-Fermi profile. We control the average bias field to about 1 mG. The confinement of the BEC in the lattice as given by L_1 gives horizontal trapping frequencies in the range of 5 to 10 Hz. We then let the atoms evolve in the lattice under the influence of the gravitational force for variable hold time T. Finally, we switch off the horizontal confinement and ramp the lattice depth adiabatically to zero within 300 μs to measure the momentum distribution by the standard time-of-flight technique, taking an absorption picture on a CCD camera. For some of the data, we turn on the magnetic levitation field to allow for longer expansion times up to 100 ms. To minimize broadening of the distribution as a result of interaction, we switch the scattering length to zero during the release and the initial time-of-flight.

We observe persistent Bloch oscillations when minimizing the effect of interactions at a magnetic field value of 17.12 G (see below). Figures 1(a)–1(d) show the evolution of the momentum distribution during the first, the 1000th, the 10 000th, and the 20 000th Bloch cycle. Initially, the momentum distribution exhibits narrow peaks. Their full width Δp [17] is as narrow as about $0.15\hbar k$, where $k = 2\pi/\lambda$. Very little broadening along the vertical direction is seen after the first 1000 cycles. Initial excitation of horizontal motion as a result of ramping the power in L_2 and switching the scattering length leads to some horizontal spreading. After 20 000 cycles, the distribution has started to spread out noticeably along the vertical direction.

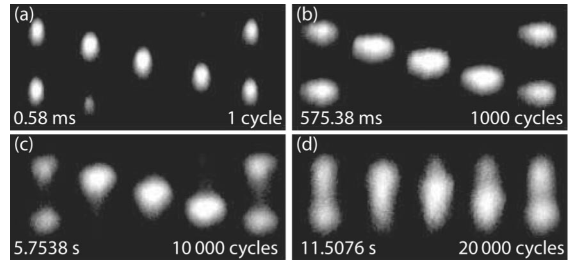

FIG. 1. Long-lived Bloch oscillations for a noninteracting BEC with Cs atoms in the vertical lattice under the influence of gravity. Each picture shows one Bloch cycle in successive time-of-flight absorption images corresponding to the momentum distribution at the time of release from the lattice. Displayed are the first (a), the 1000th (b), the 10 000th (c), and the 20 000th (d) Bloch cycle for minimal interaction near the zero crossing for the scattering length.

Figure 2 highlights the high number of Bloch oscillations, which we can observe for the case of minimal interaction strength. It shows how the strongest peak of the momentum distribution cycles through the first Brillouin zone with the typical sawtooth behavior [8]. More than 20 000 cycles can easily be followed. From a fit to the data, we determine the Bloch period to 0.575 380 7(5) ms. Assuming that no additional forces act on the sample, the local gravitational constant is $g = 9.803\,821(9)$ m/s^2. The error is statistical only. While we took care to minimize magnetic field gradients, we expect them to be the dominant contribution to the systematic error.

In order to quantify the dephasing of Bloch oscillations, we determine for each Bloch period the width Δp of the momentum distribution at the instant in time when the peak of the distribution is centered at zero momentum, i.e., for the central picture of each series shown in Fig. 1. Figure 3(a) displays Δp up to the 300th Bloch cycle for different interaction strengths ranging from 0 to 300 a_0. For minimal interaction strength ($a \approx 0$ a_0), we see no broadening of the distribution. Broadening can clearly be

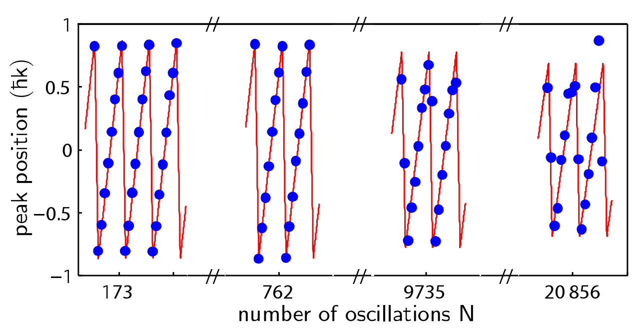

FIG. 2 (color online). Position of the strongest peak in the momentum distribution as a function of the number N of Bloch oscillations (dots). More than 20 000 cycles can be followed with high contrast. A fit to the data (solid curve) yields a Bloch period of 0.575 380 7(5) ms.

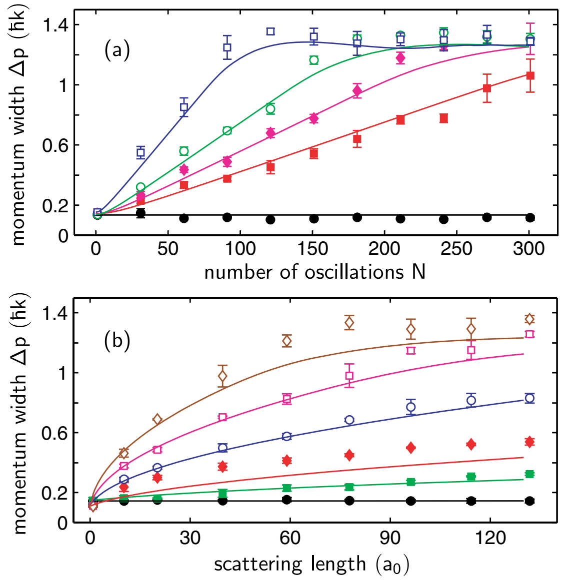

FIG. 3 (color online). Width Δp of the momentum distribution for different interaction strengths. (a) Evolution of Δp as a function of the number N of Bloch cycles for different values of the scattering length ($a = 0$, 25, 50, 100, and $300 a_0$ from bottom (full circles) to top (open squares). The solid curves are derived from a numerical model calculation, see text. (b) Width Δp for a fixed number of cycles $N = 1$ (full circles), 25 (full squares), 50 (full diamonds), 100 (open circles), 150 (open squares), and 200 (open diamonds) as a function of scattering length. The solid line represents the model calculation. All error bars correspond to $\pm$ 1 standard deviation resulting from 7 measurements. The data and the simulations correspond to the following parameters: lattice depth: $7.9 E_R$, scattering length during lattice loading: 210 a_0, trapping frequencies in L_1 and L_2: 10 and 8 Hz, atom number in the BEC: 5×10^4.

seen for $a = 25\ a_0$, and the rate of broadening then increases with increasing interaction strength. For $a \geq 50\ a_0$, the width Δp saturates within the chosen observation time to a value of about $1.3\hbar k$ as the momentum distribution completely fills the first Brillouin zone [18]. To a good approximation, we find that Δp initially increases linearly with time. In Fig. 3(b), we plot Δp as a function of interaction strength for various fixed numbers of Bloch cycles. Δp appears to scale with the square root of the interaction strength. Both observations agree well with a simple model for the dephasing of Bloch oscillations, which predicts $\Delta p \propto \sqrt{a} T$ [19] for sufficiently short times T. In order to verify this model, we have performed numerical calculations solving the one-dimensional Gross-Pitaevskii equation in the presence of an optical lattice under the influence of gravity for the typical parameters of our experiment according to the method detailed in Ref. [20]. Via Fourier transform of the spatial wave function, we determine the momentum distribution and its width. As shown in Fig. 3 (solid lines), we find very good agreement with our measurements with no adjustable parameters when we add a constant offset of $0.1\hbar k$ to all the numerical curves. This offset takes into account residual interactions during release from the lattice as a result of the finite magnetic switching speed, which leads to some artificial broadening of the distribution. We attribute the systematic discrepancy for the $N = 50$ data in Fig. 3(b) to the horizontal motion which leads to modulations in the density that adds a modulation onto Δp also seen in Fig. 3(a).

To find the value for the magnetic field that gives minimal broadening, we measure Δp after 6951 cycles in the vicinity of the crossing. Figure 4 plots Δp as a function of magnetic field. It shows a clear minimum, which we expect to correspond to the zero crossing for the scattering length. From a Gaussian fit, we determine the center position of the minimum to be at 17.119(2) G. The one-sigma error takes into account our statistical error in magnetic field calibration. To our knowledge, this is the most precise determination of a minimum for the elastic cross section in ultracold atom scattering. We believe that our measurements are limited by the ambient magnetic field noise, leading to a finite width for the distribution of the scattering length. In fact, a reduction of the atomic density gives longer decay times for the Bloch oscillations. Note that in the scattering length regime considered here, the effect of the (magnetic) dipole-dipole interaction [21] should start to play a role.

Our capability to observe Bloch oscillations on extended time scales without interaction-induced dephasing allows us to study the effect of deliberately imposed dephasing. For this, we apply a linear force gradient ∇F corresponding to harmonic trapping at $\nu = 40(1)$ Hz along the vertical direction by turning on laser beam L_2 during the hold time. Figure 5 shows the widths Δp for two cycle phases separated by π as a function of the number N of Bloch cycles. The two phases correspond to the single- resp.

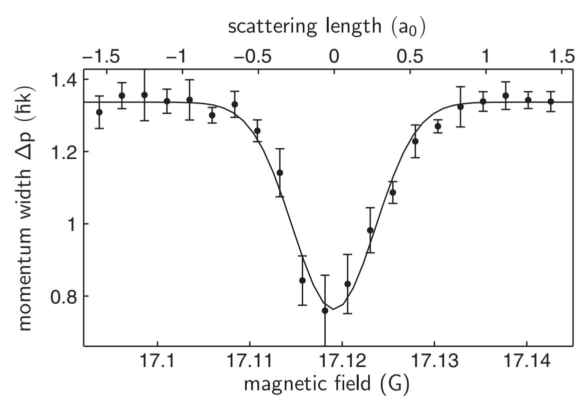

FIG. 4. Broadening of the momentum distribution as a result of 6951 Bloch oscillations near the zero crossing for the scattering length. The width Δp is plotted as a function of magnetic field (dots). The solid line is a Gaussian fit with a rms-width of 4.5 mG. The fit is centered at 17.119(2) G. The zero for the scattering length scale on top was chosen to agree with this value.

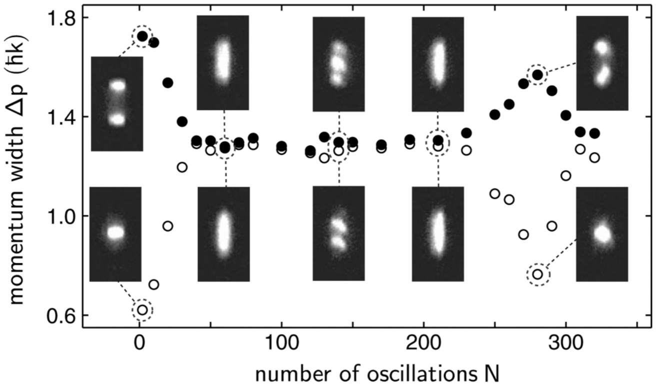

FIG. 5. Collapse and revival of Bloch oscillations for the case of a noninteracting BEC with a vertical force gradient. The width Δp is plotted as a function of the number N of Bloch cycles for two cycle phases separated by π. For selected cycles ($N = 1$, 70, 140, 210, and 280), two absorption images corresponding to the two cycle phases are shown.

symmetric double-peaked distribution. Both widths rapidly increase resp. decrease to the same value of $1.3\hbar k$ within about $N = 30$ oscillations. Here the ensemble is dephased. It then remains dephased for about 200 cycles. Partial rephasing at intermediate times not reflected in the widths can be seen from the absorption images. Revival of the oscillations [22] happens around $N = 280$ when the values for both widths separate again [23]. This number agrees well with the expected value of $N_{\rm rev} = 292(15)$ given by $N_{\rm rev} = F_{\rm grav}/(\nabla F d) = mg/(m\omega^2 d)$, where $F_{\rm grav}$ is the gravitational force, $\omega = 2\pi\nu$, and $d = \lambda/2$ is the lattice spacing. Subsequently, the widths collapse again to the common value. In further measurements, we see up to four collapses and revivals.

In summary, we have demonstrated the control of interaction-induced dephasing near a zero crossing for the scattering length. On the crossing, we have realized a noninteracting BEC, which allows us to observe more than 20 000 Bloch cycles, indicating a matter-wave coherence time of more than 10 s. The broadening of the momentum distribution agrees well with results from theoretical models. We believe that the number of observable Bloch cycles is limited by residual interactions as a result of magnetic field noise. Our results open up exciting new avenues for precision measurements with quantum-degenerate gases. For example, it is now possible to perform sensitive measurements of forces on short length scales, such as the Casimir-Polder force near a dielectric surface [24]. Future experimental work can now address the nature of the dephasing [25] by studying structure in the momentum distribution.

A similar experiment on long-lasting Bloch oscillations and control of the interaction strength has recently been performed with a BEC of ^{39}K atoms at LENS, Italy [26]. We thank A. Daley for theoretical support and for help with setting up the numerical calculations and A. Buchleitner and his group for useful discussions. We are grateful to A. Liem and H. Zellmer for valuable assistance in setting up the 1064 nm fiber amplifier system. We acknowledge contributions by P. Unterwaditzer and T. Flir during the early stages of the experiment. We are indebted to R. Grimm for generous support and gratefully acknowledge funding by the Austrian Ministry of Science and Research (BMWF) and the Austrian Science Fund (FWF).

[1] S. A. Diddams *et al.*, Science **306**, 1318 (2004).
[2] S. Bize *et al.*, J. Phys. B **38**, S449 (2005).
[3] M. M. Boyd *et al.*, Phys. Rev. Lett. **98**, 083002 (2007).
[4] A. Peters, K. Y. Chung, and S. Chu, Nature (London) **400**, 849 (1999).
[5] P. Cladé *et al.*, Phys. Rev. Lett. **96**, 033001 (2006).
[6] S. Gupta *et al.*, Phys. Rev. Lett. **89**, 140401 (2002).
[7] For a review, see T. Köhler, K. Góral, and P. S. Julienne, Rev. Mod. Phys. **78**, 1311 (2006).
[8] M. Ben Dahan *et al.*, Phys. Rev. Lett. **76**, 4508 (1996).
[9] R. Battesti *et al.*, Phys. Rev. Lett. **92**, 253001 (2004).
[10] G. Ferrari *et al.*, Phys. Rev. Lett. **97**, 060402 (2006).
[11] O. Morsch *et al.*, Phys. Rev. Lett. **87**, 140402 (2001).
[12] G. Roati *et al.*, Phys. Rev. Lett. **92**, 230402 (2004).
[13] T. Weber *et al.*, Science **299**, 232 (2003).
[14] T. Kraemer *et al.*, Appl. Phys. B **79**, 1013 (2004).
[15] P. Julienne (private communication).
[16] A. Liem *et al.*, Opt. Lett. **28**, 1537 (2003).
[17] We define the full width Δp to be the root-mean-square (rms) diameter of the distribution.
[18] The momentum distribution of a fully dephased interacting ensemble carries high-contrast substructure which will be discussed in a forthcoming publication.
[19] D. Witthaut *et al.*, Phys. Rev. E **71**, 036625 (2005). Note that for the quasi-one-dimensional case, the interaction constant in Eq. (33) is proportional to $\sqrt{a}$, see [20].
[20] A. Smerzi and A. Trombettoni, Phys. Rev. A **68**, 023613 (2003).
[21] S. Giovanazzi, A. Görlitz, and T. Pfau, Phys. Rev. Lett. **89**, 130401 (2002).
[22] A. V. Ponomarev and A. R. Kolovsky, Laser Phys. **16**, 367 (2006).
[23] Note that the revived Bloch cycles are subject to a phase shift, which depends on the vertical location of the harmonic trap minimum with respect to the lattice minima.
[24] I. Carusotto *et al.*, Phys. Rev. Lett. **95**, 093202 (2005).
[25] A. Buchleitner and A. R. Kolovsky, Phys. Rev. Lett. **91**, 253002 (2003).
[26] M. Fattori *et al.*, Phys. Rev. Lett. **100**, 080405 (2008).