Atom Interferometry with a Weakly Interacting Bose-Einstein Condensate

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(Received 26 October 2007; published 28 February 2008)

We demonstrate the operation of an atom interferometer based on a weakly interacting Bose-Einstein condensate. We strongly reduce the interaction induced decoherence that usually limits interferometers based on trapped condensates by tuning the s-wave scattering length almost to zero via a magnetic Feshbach resonance. We employ a ^{39}K condensate trapped in an optical lattice, where Bloch oscillations are forced by gravity. The fine-tuning of the scattering length down to 0.1 a_0 and the micrometric sizes of the atomic sample make our system a very promising candidate for measuring forces with high spatial resolution. Our technique can be in principle extended to other measurement schemes opening new possibilities in the field of trapped atom interferometry.

DOI: 10.1103/PhysRevLett.100.080405 PACS numbers: 03.75.Dg, 03.75.Gg, 03.75.Lm

A Bose-Einstein condensate (BEC) is the ideal candidate for atom interferometry because it offers the ultimate control over the phase and amplitude of a matter wave. Its macroscopic coherence length [1] allows high phase contrast in interferometric experiments. Its confinement in atomic traps or waveguides can lead to the realization of atom interferometers with high spatial resolution [2,3]. Unfortunately in high density trapped condensed clouds, interaction induces phase diffusion [4] and can cause systematic frequency shifts due to uncontrolled atomic density gradient, thus seriously limiting the performances of a BEC atom interferometer. In order to avoid the deleterious effect of interaction, atom interferometers for high precision measurement use free falling dilute samples of nondegenerate atoms [5]. The main drawbacks are the limited interrogation time (0.5 s) due to the finite size of the apparatus and the poor spatial resolution of this type of sensors. Using fermionic atoms instead of bosons represents one possibility to have access to trapped interferometry with a degenerate gas [6]. In fact, because of the Pauli exclusion principle, the atomic scattering cross section at sufficiently low temperatures is fully suppressed. However, the quantum pressure limits the spatial resolution, and the momentum spread reduces the interference contrast. Another way to reduce the effect of the interaction is to realize a number squeezed splitting [7,8]. In this way, coherence times are increased at the expense of the interference signal visibility. Despite the fundamental limit represented by interaction induced decoherence, several groups are performing experiments with trapped BECs [7–10], in the challenging search for the "ideal" interferometer.

In this Letter, we demonstrate the conceptually simplest solution to the long-standing problem of interaction induced decoherence in BEC interferometers. We show how, by properly tuning the interaction strength in a quantum degenerate gas of ^{39}K [11] by means of a broad magnetic Feshbach resonance [12], we can greatly increase the coherence time of an atom interferometer. By achieving almost vanishing values of the s-wave scattering length, we demonstrate trapped atom interferometry with a weakly interacting BEC.

The interferometer we adopted, commonly known as Bloch oscillations interferometer, is based on a multiple well scheme [2,6,13,14]. The condensate is adiabatically loaded in a sinusoidal potential with period $\lambda/2$, realized with an optical standing wave of wavelength λ. In the presence of an external force F, the macroscopic wave function ψ of the condensate can be described as a coherent superposition of Wannier Stark states ϕ_i [15], parametrized with the lattice site index i, characterized by complex amplitudes of module $\sqrt{\rho_i}$ and phase θ_i, $\psi = \sum_i \sqrt{\rho_i} \exp(j\theta_i)\phi_i$ [16]. In the absence of interaction, the phase of each state evolves according to the energy shift induced by the external potential, i.e., $\theta_i = F\lambda it/2\hbar$. By releasing the cloud from the lattice, the macroscopic interference between different Wannier Stark states gives rise to the well known Bloch oscillations of the density pattern, with period $t_{\text{bloch}} = 2h/F\lambda$. A measurement of the frequency of such oscillations allows a direct measurement of the external force. Generally, interactions give rise to a complex system of nonlinear equations for ρ_i and θ_i. In the weakly interacting limit, the ρ_i do not change and, in addition to θ_i, extra phase terms θ_i', proportional to the local interaction energy, are accumulated, i.e., $\theta_i' \propto a_s \rho_i t$, where a_s is the atomic scattering length. This causes phase diffusion and destruction of the interference pattern. In this Letter, we demonstrate that by tuning a_s almost to zero, it is possible to reduce the values of θ_i' and extend the coherence time of the interferometer.

Our experimental apparatus has been described in detail elsewhere [11]. Using sympathetic cooling with ^{87}Rb and other techniques similar to the ones developed for other potassium isotopes [11,17–19], we produce a ^{39}K BEC with 4×10^4 atoms in the absolute ground state $|F = 1, m_F = 1\rangle$. Because of the negative background scattering length of ^{39}K ($a_{\rm bg} = -33\ a_0$), the final stage of evaporation is performed in a crossed optical dipole trap at a magnetic field of 395 G. At this field, a broad Feshbach resonance (width of the resonance $\Delta = -52$ G, center of the resonance $B_c = 402.4$ G [12]) allows the homo-nuclear scattering length of K to be large and positive ($\approx 200\ a_0$) and a stable condensate can form. Taking into account the dependence of a_s on the magnetic field $a_s(B) = a_{\rm bg}\{1 - [\Delta/(B - B_c)]\}$, the possibility of tuning with high accuracy the interaction from repulsive to attractive is evident. In particular, around $B_{zc} = B_c + \Delta$, i.e., the point where a_s vanishes, $a_s(B) \sim a_{\rm bg}/\Delta(B - B_{zc})$ and a fine control of the scattering length ($0.6\ a_0$/G) is possible. Our magnetic field stability, better than 100 mG, allows a reduction of a_s by nearly a factor of 10^3, down to the $0.06 a_0$ level. This high degree of tunability is possible only in few other atomic species where the ratio $a_{\rm bg}/\Delta$ is favorably small [20,21].

The condensate is produced in a horizontal crossed optical dipole trap with frequencies $(\nu_x, \nu_y, \nu_z) = (85, 105, 100)$ Hz. After production of a degenerate sample, we tune a_s to the desired value in 50 ms and we load the atoms in a vertical optical lattice with depth sE_R, where $s \sim 6$ and $E_R = \hbar^2 k^2/2m$ is the recoil energy from absorption of a lattice photon ($k = 2\pi/1032$ nm), with m the mass of a potassium atom. In order to avoid an abrupt change of the horizontal confinement from the combined potential, i.e., the trap plus the lattice, to the lattice only, we apply a levitating magnetic field gradient and decrease the trapping confinement to (44, 76, 43) Hz in 40 ms. Note that the time scales for the variations of the scattering length and the external confinement have been chosen to always keep the condensate in the ground state of the trapping potential [22]. When the crossed dipole trap and the levitating field are switched off, Bloch oscillations start in the vertical lattice with radial confinement $\nu_x = \nu_y = 44$ Hz. We have intentionally chosen this rather strong confinement to work in a regime where interaction is the main source of decoherence even when a_s is reduced down to the $1 a_0$ level.

A first demonstration of our capability to extend the coherence times of the interferometer by tuning a_s is presented in Fig. 1. Here, we report the absorption images of BECs released from the lattice, after different times of oscillations performed at $100 a_0$ and $1 a_0$ scattering length. The $a_s = 100\ a_0$ measurement shows the performances of the interferometer with a typical interacting condensate. After two Bloch periods, the interference pattern is drastically broadened. Instead, the measurement with $a_s = 1\ a_0$ shows no discernible broadening on this time scale, displaying how the interaction induced decoherence can be strongly suppressed with our method.

To analyze quantitatively the effect of the tuning of the interaction, we repeat the same experimental sequence for different a_s, measuring the vertical width of the central peak at integer times of the Bloch period (Fig. 2). This study is limited to a range of values of a_s ($29\ a_0 - 1.3\ a_0$) where interaction is the main source of decoherence (see below). Notice that initially the widths increase linearly with time. This is a direct consequence of the phase terms $\theta_i' \propto a_s \rho_i t$, with $\rho_i =$ const, that evolve linearly in time [16]. Later on, when the momentum distribution of the

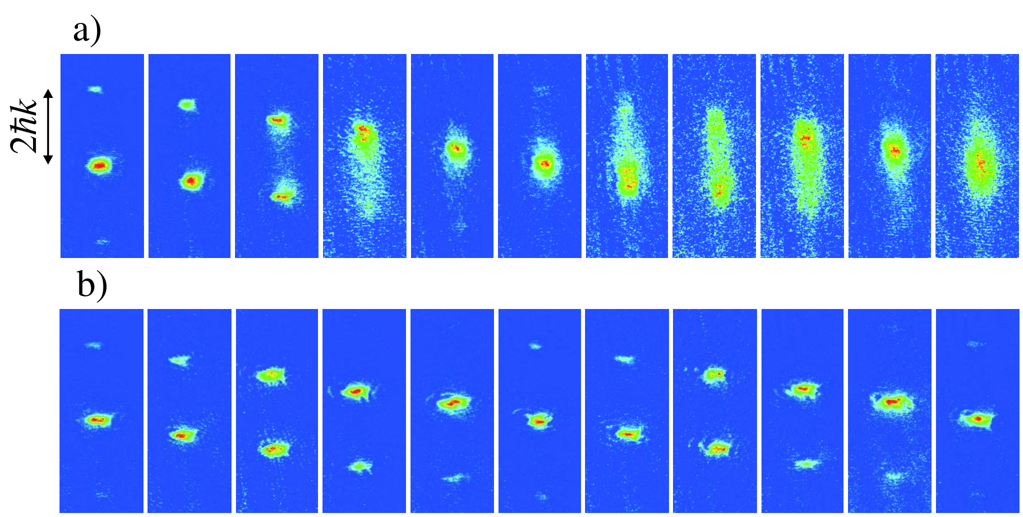

FIG. 1 (color online). Bloch oscillations from 0 to 4 ms, in steps of 0.4 ms, for a condensate with (a) $100\ a_0$ and (b) $1\ a_0$ scattering length. The picture shows absorption images of the cloud after release from the lattice. The expansion lasts 12.5 ms, and the scattering length is changed to $-33\ a_0$ only 3 ms before image acquisition.

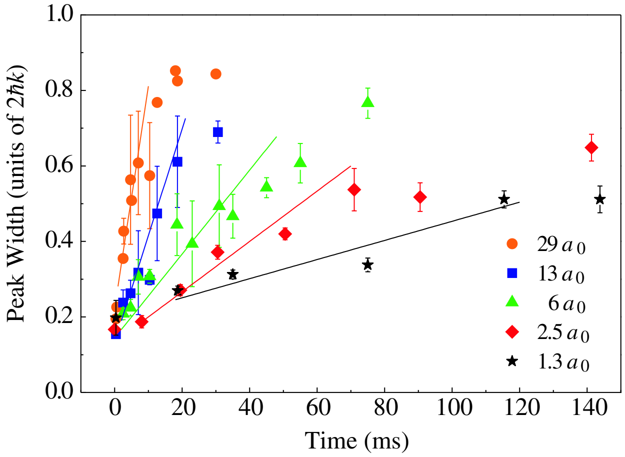

FIG. 2 (color online). Vertical $1/\sqrt{e}$ width of the central peak of the density profile as a function of the Bloch oscillation time, at integer multiples of the Bloch period after 12.5 ms of expansion from the trap. The measurement is performed for different values of the scattering length, listed on the plot, with 4×10^4 atoms on average. The lines are a fit to the data excluding the point at $t = 0$ ms, where imaging saturation effects can occur, up to times when the peak width is approximately $0.5 \times 2\hbar k$.

condensate occupies the whole first Brillouin zone, the widths saturate. From a numerical calculation of ρ_i and the theoretical analysis described in [16], we derive the interference pattern between the Wannier Stark states in the momentum space and determine the width of the central peak as a function of time. In Fig. 3, we compare the theoretical decoherence rates with the measured ones as a function of a_s. Rates are defined as the slope of a linear fit, at short times, of the curves shown in Fig. 2 in unit of $2\hbar k$. For this range of values of a_s, an almost linear behavior is found. The possibility to increase the coherence time of the interferometer by almost a factor of 100, when a_s is tuned down to $\sim 1\ a_0$, is remarkable. Notice that our theoretical analysis does not take into account the expansion of the cloud in the presence of interaction when the atoms are released from the lattice. In addition, it completely neglects energetic and dynamical instability effects [23]. These are good approximations for small values of a_s.

Below $1a_0$, a laser induced decoherence of $\sim 1\ \mathrm{s}^{-1}$ starts to significantly contribute to the evolution of the system, preventing a quantitative comparison of the observed decoherence rates with theory. We have however further investigated the effect of interaction on the decoherence of the interferometer around the zero crossing. In this region, we have used a cloud, dense enough to make the effect of the interaction visible, but sufficiently diluted in order to completely exclude the effect of three body losses (see below) and to prevent the condensate from collapse for small negative a_s [11]. A condensate with $a_s = a_{\mathrm{in}} \neq 0$ is initially prepared. Right after the beginning of Bloch oscillations, the external magnetic field is tuned to a final value in 2 ms. This value is kept constant for 180 ms of Bloch oscillations and for 12 ms of expansion from the lattice. We have probed the decoherence for two different densities that were obtained by using two different values of a_{in}, $3a_0$ and $1a_0$. In both cases, the width of the interference peak reveals a minimum at 350G (see Fig. 4). Notice that this point is in agreement with the expected position of the zero crossing (350.4 ± 0.4 G) [12]. The symmetric trend of the data confirms that the decoherence depends on the magnitude and not on the sign of the scattering length. Notice that for $a_{\mathrm{in}} = 1\ a_0$, the atoms are loaded over fewer lattice sites, resulting in larger ρ_i. In this case, a slightly larger width of the peak on the minimum is measured. This confirms that interaction induced decoherence is small but still present. The increase

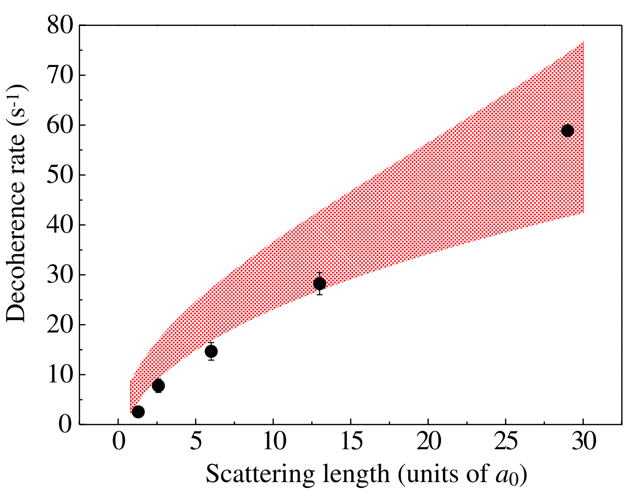

FIG. 3 (color online). Black circles indicate decoherence rates (see text) as a function of the scattering length. Rates are obtained from the slope of a linear fit, at short times, of the curves shown in Fig. 2 in unit of $2\hbar k$. The region put in evidence comes from theoretical predictions of the rates, for 2×10^4 to 5×10^4 atoms, in order to account for number fluctuations.

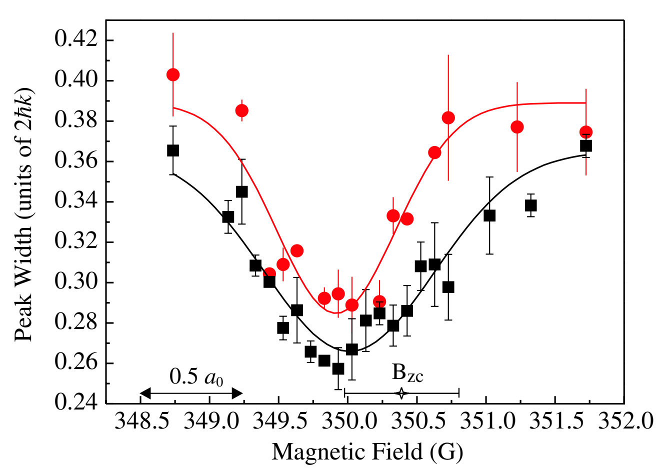

FIG. 4 (color online). Interference peak width as a function of the scattering length hold for 180 ms of Bloch oscillations. The condensate is prepared for two different values of a_s, $3a_0$ (squares) and $1a_0$ (circles), and tuned to the final value, in 2 ms, right after Bloch oscillations have started. The lines represent a Gaussian fit to the data.

in the width is compatible with our expected resolution of 0.06 a_0. Further experiments will be necessary to clarify whether dipole-dipole interaction between the magnetic dipoles of the atoms starts to play a significant role when a_s is tuned to such small values.

The possibility of tuning the scattering length allows also to control the dimensions of a trapped condensate. This can have important consequences for what concerns the spatial resolution of atom interferometers where a tunable BEC is implemented. In the following, we describe this aspect in the case of a Bloch oscillations interferometer. During Bloch oscillations, the in-trap extension of the sample results from the spatial interference of different Wannier Stark states ϕ_i. Therefore, the size of the cloud can have at most a variation of the order of the extension l of the single ϕ_i, which then set the ultimate space resolution of the interferometer. In our case, for $s = 6$ and $F = mg$, where $g = 9.8$ m/s^2, $l \sim 2$ μm [15]. This limit can be achieved preparing condensates with a size of the order of l which is possible, in our case, using typical trapping potential. To verify the in-trap size of our nearly ideal BEC, we have performed an experiment in which the condensate is prepared at $a_s = 0$ and then released from the combined potential, i.e., the trap plus the vertical lattice. In fact, the coherent splitting of the condensate over several lattice sites results in an interference pattern in the momentum space with a central peak width in units of $2\hbar k$ approximately equal to the inverse of the number of occupied sites [24]. Notice that, when $a_s = 0$, the in-trap momentum distribution is accessible experimentally because it is exactly mapped in the atomic density after a free expansion. We measure a peak width of $\approx 0.1 \times 2\hbar k$, and this corresponds to $\sim$10 sites occupied. This is in agreement with the $1/e^2$ spatial width of 4.5 μm for a condensate confined in our combined potential which has, for this measurement, a vertical trapping frequency of 100 Hz. It is important to stress that for small values of a_s, the peak density of the cloud in presence of the lattice exceeds 10^{14} atoms/cm^3. Three body losses over few hundreds of ms are negligible thanks to a low value of $K_3 = (1.3 \pm 0.5) \times 10^{-29}$ cm^6 s^{-1} for ^{39}K, that we have measured in the experiment in the zero crossing region.

The proved capability of drastically reduce the interaction induced decoherence by a fine-tuning of the scattering length, and the micrometric spatial resolution achievable (almost 1 order of magnitude better than in previous interferometers of this kind [6,25]), make our system a very promising candidate for precise measurements of Casimir Polder forces and gravitational forces between atoms and surfaces at small distances in the 1–10 μm region [25,26]. Further studies on the effect of the residual interaction on the coherence and experimental tests in a new system where technical noise is suppressed will be necessary to determine the ultimate performances of this interferometer.

In conclusion, we have performed atom interferometry with a nearly noninteracting BEC of ^{39}K. We proved that interaction induced decoherence can be suppressed by almost two orders of magnitude by tuning the scattering length almost to zero, with a broad Feshbach resonance. We expect that this technique can be extended to other interferometric schemes, opening new exciting perspectives in the field of trapped atom interferometry. We finally showed that a Bloch oscillations interferometer where a tunable BEC is implemented is a promising candidate for measurements of forces at small distances from surfaces.

While writing this manuscript, we became aware of a similar work performed with ^{133}Cs in Innsbruck [27].

We acknowledge contributions by F. Marin, discussions with A. Simoni, A. Smerzi, S. Stringari, and the rest of the quantum gases group at LENS. This work was supported by MIUR (PRIN 2006), EU (MEIF-CT-2004-009939), INFN, Ente CRF, and Int. Proj. SCALA.

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