

Effect of Optical Disorder and Single Defects on the Expansion of a Bose-Einstein Condensate in a One-Dimensional Waveguide

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We investigate the one-dimensional expansion of a Bose-Einstein condensate in an optical guide in the presence of a random potential created with optical speckles. With the speckle the expansion of the condensate is strongly inhibited. A detailed investigation has been carried out varying the experimental conditions and checking the expansion when a single optical defect is present. The experimental results are in good agreement with numerical calculations based on the Gross-Pitaevskii equation.

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The study of Bose-Einstein condensates (BECs) in random potentials has gained much interest in recent years. Interesting phenomena can be studied in the context of wave transport in random systems, such as Anderson localization in which transport is dramatically suppressed due to disorder. Anderson localization was first proposed to explain the metal-insulator transition in electron transport in disordered solids [1,2] and later predicted [3] and observed [4] also for other wave phenomena such as light and sound. The fundamental concept of Anderson localization applies to any wave phenomenon and should be observable for ultracold atoms as matter waves propagating in a random potential.

One-dimensional (1D) random systems are excellent for the observation of Anderson localization as has been shown for optical waves [5]. In cold Bose gases, due to the presence of interactions and thanks to the demonstrated possibility to create the Mott insulator state in a deep optical lattice [6], the range of interesting and new effects increases, including the Bose-glass phase and spin glasses [7]. Different theoretical papers have already addressed these problems [8–11] and a first experimental study has been reported in [12].

In this Letter we present an experimental study of a BEC expanding in a 1D optical guide in the presence of a random potential created by optical speckles. We find that in the speckle potential the 1D expansion is strongly suppressed. In order to understand the role played by the disorder we also study the BEC expansion when only a single defect is present. Numerical calculations based on the Gross-Pitaevskii equation (GPE) are in perfect agreement with the experimental results.

We first produce a BEC of $\approx 2 \times 10^5$ ⁸⁷Rb atoms in a Ioffe-Pritchard magnetic trap with axial and radial frequencies $\omega_z = 2\pi \times (8.74 \pm 0.03)$ Hz and $\omega_{\perp} = 2\pi \times (85 \pm 1)$ Hz respectively, with the axis of the trap oriented horizontally. Then we adiabatically transfer the condensates into a crossed optical dipole trap with the same elongated symmetry as the magnetic trap. The optical trap is made

from two orthogonal beams derived from a Ti:Sa laser working at 830 nm (far red detuned with respect to the atomic transition at 795 nm). The horizontal beam, shone along the axial direction of the condensate, has a waist of 40 μm and a typical power of 40 mW while the vertical beam is characterized by a waist of 130 μm and a typical power of 50 mW. The measured trapping frequencies of the optical trap are $\omega_{\text{OT}_z} = 2\pi \times (24.7 \pm 0.8)$ Hz in the axial direction and $\omega_{\text{OT}_{\perp}} = 2\pi \times (293 \pm 6)$ Hz in the radial direction. The two beams are derived from the same laser and pass through acousto-optic modulators (AOMs) working at different frequencies (with a difference of 7 MHz). We switch on the crossed dipole trap adiabatically using a 200 ms exponential ramp with a time constant of 50 ms. After an additional time interval of 100 ms we switch off the magnetic trap in order to leave the condensate in the pure optical trap and wait 1 s to let the system equilibrate to the ground state. The transfer efficiency from the pure magnetic trap to the pure optical trap is $\sim 50\%$, corresponding to a condensate of $\sim 10^5$ atoms with a chemical potential $\mu/h \approx 2.5$ kHz and typical radii (calculated in the Thomas-Fermi regime) of $R_z = 30 \mu\text{m}$ and $R_{\perp} = 2.6 \mu\text{m}$ in the axial and radial direction.

In order to induce a 1D expansion of the condensate, we switch off abruptly (in less than 1 ms) the vertical trapping laser beam. The horizontal laser beam results in an optical guide, the axial frequency being $\approx 2\pi \times 1$ Hz. Furthermore, the optical guide is tilted by 8.6 ± 1.6 mrad with respect to the horizontal plane resulting in a measured acceleration along the guide, $a = 0.096 \pm 0.004$ m/s², caused by gravity.

We observe the expansion of the BEC in the random potential adding optical speckles [13] that are obtained and characterized as described in our previous work [12]. The beam to produce the speckles is derived from the same Ti:Sa laser we use to create the dipole trap, but passed through a different AOM (with a detuning of 10 and 17 MHz from the AOMs controlling the crossed dipole trap) in order to have an independent control on its time

switching. The speckle beam, after passing through a diffusive plate, propagates along the horizontal radial direction of the condensate and is collinear with the resonant laser beam used for the imaging of the condensate. The imaging setup can be used to detect both the BEC and the speckle pattern, enabling us to characterize the actual random potential experienced by the condensate [12]. The Fourier transform of the speckle potential indicates that the smallest length scale of the speckle is $10 \mu\text{m}$ [14], much bigger than the radial size of the condensate. Therefore, the condensate experiences the varying random potential only along the optical guide axis during expansion. We define the speckle height V_S by taking twice the standard deviation of the speckle potential along the BEC axial direction. The speckle height and the other energy scales will be conveniently expressed throughout this Letter in units of frequency (with the implicit assumption of a division by the Planck constant \hbar).

In a first series of measurements we adiabatically switch on the speckle potential together with the crossed dipole trap in order to let the condensate equilibrate to the ground state of the combined potential. In Fig. 1 we report the rms radius and the center of mass of the atomic cloud expanding in the optical guide once the vertical trap beam has been switched off as a function of time for different speckle potential heights. Without speckles the condensates freely expand, while in the presence of the speckles both the expansion and the center of mass motion are inhibited after few hundreds of ms for $V_S/\mu > 0.3$.

In Fig. 2(a) we report the density profile of the condensate, imaged *in situ* in the optical guide, after 118 ms of expansion for different speckle potential heights (ranging from $V_S/\mu = 0$ to 0.7) together with the picture of the actual speckle field used. A closer look shows that actually two different components can be distinguished: while a low density cloud expands without stopping, a few localized density peaks are observable. In the same figure we also show the measured density distribution obtained releasing the BEC ground state from the crossed dipole trap + random potential. The expansion

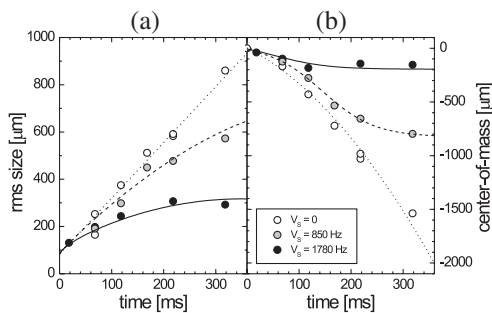


FIG. 1. (a) rms radius of the condensate expanding in the optical linear guide + speckle potential as a function of time for three different values of the speckle height with $V_S/\mu < 1$. (b) Corresponding center of mass motion. The lines are guides for the eyes.

from the highest speckle potential of 1.8 kHz shows a broad Gaussian profile that is compatible with interference from separate, randomly distributed condensates [12], as one would expect in the tight binding regime. For lower speckle potential only density modulations of the Thomas-Fermi profile are observed, indicating that for $V_S < 1.2$ kHz we are not in the tight binding regime. However, we still observe a halting of the expansion in the linear guide.

In order to have further insight into the mechanism causing the suppression of transport, we repeat the experiment either putting the speckle pattern to one side of the crossed dipole trap center, or switching on the speckle abruptly to reduce trapping in the deepest speckle wells. In this latter case, we switch on the speckle only after 50 ms of free expansion in the linear guide. This preliminary expansion allows a reduction of the interaction energy to 30% of the initial value and produces a bigger axial size corresponding to a larger number of speckle peaks (≈ 50) across the condensate. Because of the acceleration along the optical guide, when the speckle potential is added, the kinetic energy of the condensate center of mass is 2.5 kHz. In Fig. 2(b) we show the density distribution of the condensate after 300 ms of expansion for two different positions of the same speckle realization with $V_S = 2$ kHz. We still observe a transport inhibition that is characterized by peaks in the density distribution that seem correlated to the

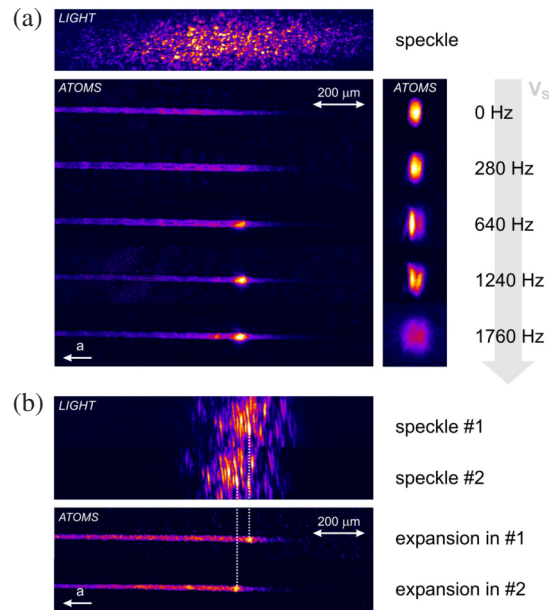


FIG. 2 (color online). (a) left: picture of the speckle potential and *in situ* density profiles of the condensate after 118 ms of expansion in the linear guide for $0 < V_S < 1.7$ kHz. right: density profile of the condensate released from the crossed dipole trap + speckle potential after 18 ms of free expansion. (b) For two different positions of the speckle field we show the density distribution of the atomic cloud after 300 ms of expansion in the linear optical guide with the speckle switched on abruptly and $V_S = 2$ kHz.

position of the speckles potential (as shown by dashed lines in the figure).

In order to investigate this correlation, we perform a series of experiments when a single defect, instead of a randomly distributed series, is present. The single defect is obtained by removing the diffusive plate and focusing the beam onto the condensate. This creates a single optical well (with an elongated shape obtained using a cylindrical lens) whose size and depth V_w are obtained through a Gaussian fit. The size of the well is $\sigma_z = 6 \mu\text{m}$ along the horizontal direction and $\sigma_y = 85 \mu\text{m}$ along the vertical direction. We study the expansion of the condensate in the linear guide with the single defect with the same time sequence used for the speckles potential: either switching on the single defect adiabatically together with the crossed trap, or abruptly after a preliminary expansion in the linear guide. The observed density profiles are reported in Fig. 3(a). While a low density component expands freely, a sharp peak in the density profile can be observed corresponding to part of the condensate trapped in the single defect and seems very similar to the effect seen with the speckles. The population of atoms localized in the single well increases as a function of the well depth as shown in Fig. 3(b). The efficiency of trapping is reduced when the well is switched on abruptly but we still have some trapping for $V_w \geq 1 \text{ kHz}$, corresponding to a depth of the single well comparable with the speckle potential that stops the expansion of the condensate. These results indicate that in our experiment the effect of trapping in the deepest wells of the random potential cannot be avoided even in a regime of $V_w < \mu$.

Our observations are supported by numerical calculations based on the GPE. As in the experiment we consider both the case of a random potential with correlation length $2\sigma_z = 10 \mu\text{m}$ and a single Gaussian well. Moreover, in order to better enlighten the actual role played by randomness, we also consider the case of a periodic potential with the same spacing and height of the speckles. The conden-

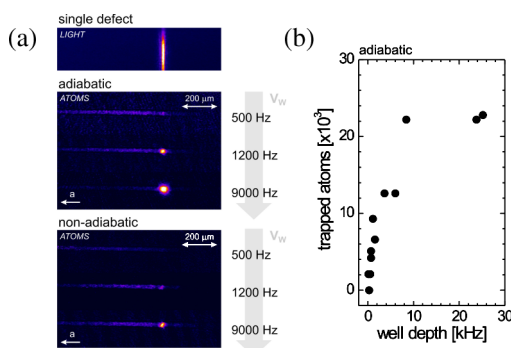


FIG. 3 (color online). (a) Intensity profile of the laser beam creating the single defect and density profiles of the condensate after 300 ms of expansion for $500 \text{ Hz} < V_w < 9.0 \text{ kHz}$ either adiabatically or abruptly adding the defect. (b) Number of atoms trapped in the single defect as a function of V_w when the potential well is switched on adiabatically.

sate is initially prepared in the ground state of the combined potential, and then allowed to expand through the optical guide (neglecting for simplicity gravity). The density profiles after 75 ms of expansion are shown in Fig. 4. In all the cases two components are clearly identified: the lateral wings that expand almost freely, and a central part that is localized in the deepest wells of the potential. The comparison between these different situations indicates that the observed effect is mainly due to deep wells in the potential acting as single traps when the local chemical potential becomes of the order of their height. This could mask the possible observation of other localization effects due to the cumulative behavior of the disordered potential wells. The theoretical predictions are in perfect agreement with the experimental observations. Note also that in this regime interactions play mainly against localization since they provide the initial energy that allows the wings to expand, whereas the dephasing that it is produced in the central part is only a secondary effect [15].

The system we have realized can be used to deeply investigate the interaction between a condensate and a single scatterer. Anderson localization is due to interference between partially reflected matter waves from randomly distributed scatterers. Although interactions in a condensate may destroy Anderson localization, experimental studies with a single defect can be very useful to understand if the random potential created by light is a proper tool to observe this effect even in absence of interactions, for instance, working with fermions.

In this context we investigate the transmission/reflection of a moving condensate “colliding” with a single optical defect. We induce axial dipole oscillation of the condensate confined in the harmonic magnetic trap [16] adding a single optical well as shown in Fig. 5. Varying the distance of the defect from the center of the magnetic trap and the amplitude of the oscillation, we can finely tune the center of mass kinetic energy of the condensate. Considering a

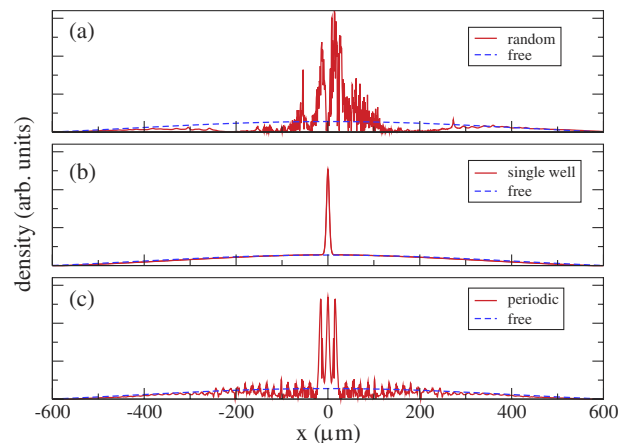


FIG. 4 (color online). Calculated density profiles after 75 ms of expansion for random potential (a), single Gaussian well (b), and periodic potential (c), compared with the free expansion case (dashed line). In all three cases the potential height is 0.4μ .

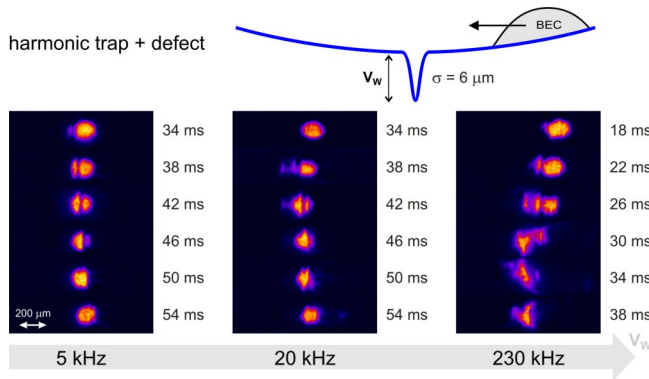


FIG. 5 (color online). Top: Schematic of the experiment. Bottom: Density profiles of the condensate performing dipole oscillations in the magnetic trap and interacting with a single well.

single particle moving at constant velocity, in order to observe quantum reflection of the matter wave from a single well two different conditions have to be fulfilled [17]. The first condition regards the comparison between the kinetic energy of the particle E_k that should be smaller than the depth of the well $|V_w|$. This condition is the only requirement in the case of a square well, but for different shapes of the well a second condition becomes important. The potential should vary more than E_k in a distance short compared to the de Broglie wavelength of the particle λ_{dB} , i.e., the following relation should hold: $|dV_w/dz|\lambda_{dB} > E_k$. When near-infrared light is used to create the defects, this condition becomes very difficult to fulfill. The optical access in standard BEC apparatus limits the size of light defects to several microns resulting in the requirement of intense light or very low condensate velocities. Very deep optical potentials can induce heating of the atomic cloud. In our experiment, to check the temperature of the system, we have performed the imaging of the condensate after a free expansion of 18 ms.

In Fig. 5 we show a series of images corresponding to the condensate performing dipole center of mass oscillations in the harmonic magnetic potential and interacting with a single well. In the experiment we vary the time after the excitation of the dipole motion and the depth of the optical well. For $V_w < 200$ kHz when the condensate approaches (with a center of mass kinetic energy $E_k \approx 5$ kHz) the potential well at $t \approx 40$ ms a hole in the density distribution forms due to the fast acceleration induced by the potential slope. The condensate recovers its starting density distribution after crossing the well. In this regime of parameters, as expected, we do not observe a quantum reflected component. As we increase the depth of the well to $V_w \geq 200$ kHz the condensate starts to be destroyed by the interaction with light. These observations demonstrate that it seems quite challenging to see such quantum effects in the interaction of the condensate with a series of defects created with light.

In conclusion, we have experimentally studied the 1D expansion of a BEC in a linear optical guide in the presence

of a random potential. The random potential is created by a speckle field that has been switched on either adiabatically or abruptly after some initial expansion of the condensate. In both the cases we have observed a halted expansion of the atomic cloud and the suppression of the center of mass motion. In order to understand the role played by randomness in this behavior we have repeated the same experiments with a single defect created by a tightly focused laser beam. The experimental results are confirmed by GPE simulations showing that the suppressed expansion is mainly caused by trapping in the deepest wells of the potentials. We have also carried out a detailed investigation of a BEC performing center of mass oscillations in a harmonic trap interacting with a single optical well. The reported measurements indicate that the diffraction limited size of defects created by light poses severe restrictions on the range of parameters necessary to observe quantum reflection or transmission that is at the basis of Anderson localization of matter waves.

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