

Detection of phase randomization in a chain of Bose condensates

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Abstract. Interference in a long chain of Bose condensates is observed. Spatially quasi-periodic interference pattern appears even when the phases of the condensates are uncorrelated. However, the spatial fringe period depends qualitatively on whether the adjacent condensates are in phase or not. This is used for measuring the degree of phase coherence.

Chain of interfering elements is a paradigmatic model in several areas of physics. The relative phases of the field in each element determine the stationary state and the dynamics of the chain. The evolution of a chain with equal phases was studied in optics back in 1836 [1]: in the free space, the electromagnetic field from a chain of identical sources reassumes its initial form after certain propagation distance, which is presently referred to as the Talbot effect. Similar effects are observed in vacuum electronics, acoustics, plasmonics, and matter-wave optics. For matter fields the effect may be seen in the time domain, without propagation.

Solid state physics offers a variety of situations, where the phase of each element fluctuates either due to thermal effects or purely quantum reasons. In the Josephson junction chains such fluctuations drive phase transitions between superconducting and isolating states [2, 3]. Phase slips and the resulting negative interference may prevent the electric current from flowing through the chains. Another example of a chain is high-temperature superconductors, which are composed of layered structures. In systems composed of thin layers, the phase may also fluctuate in the layer plane. The amount of in-plane fluctuations signals transitions between Bose-condensed state, non-condensed Berezinskii-Kosterlitz-Thouless superfluid [4, 5], and the normal state.

The most direct information about the phases in the chain elements is obtained in interference experiments. In solids, where most interesting problems are encountered, the ability to observe interference is far below that in optics. In experiments with ultracold atoms and molecules, along with other interesting physics [6, 7], one may observe the effects known from solid state physics [8, 9, 10]. This is combined with direct observation of matter-wave interference [11].

Here, in experiment with ultracold bosonic molecules, we show that for a chain of randomly phased fields, the spatial quasi-order appears shortly after the onset of the free evolution. Within a simple model, we show that the spatial periodicity is the direct consequence of disordered phases. The spatial period differs from that of the original Talbot effect. Therefore, from the spatial period of the interference one may distinguish whether the initial state of the chain was ordered or not. Moreover, for partially disordered phases two effects combine: One may see the



Talbot effect on top of the disordered-phase interference. From the relative strength of the two effects one may judge the degree of the phase disorder.

In experiments we use a chain of molecular Bose-Einstein condensates (BECs) trapped in a one-dimensional optical lattice as shown in figure 1. Each cloud is a kinematically two-dimensional (2D) system, where most of the molecules occupy the lowest state of motion along the lattice and many states of motion along the layers. In uniform 2D systems the Bose condensation is prohibited at $T > 0$. However, in a harmonic potential a noninteracting Bose gas may condense at finite temperatures. In a repulsive BEC, a molecule locally sees a flat potential, which is the sum of the harmonic trap and the repulsive mean field. From the straight interference fringes we judge that the gas condenses at relatively high temperatures.

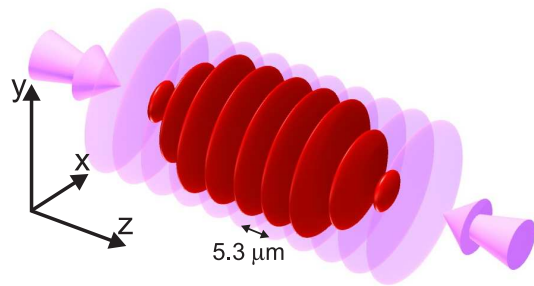


Figure 1. Trapping ultracold atoms in antinodes of a standing optical wave. The isolated clouds of atoms shown in dark red, the standing-wave intensity shown in light purple.

The experimental setup is similar to that of Ref. [12] and references therein. The bosons are weakly-bound Li_2 molecules in a long-lived excited vibrational state, each composed of two fermionic ^6Li atoms. A series of BECs is prepared in an optical lattice potential formed by two counter-propagating laser beams of wavelength $10.6 \mu\text{m}$. The maxima of the standing-wave intensity are the minima of the potential. Weak transverse confinement appears due to the Gaussian shape of the mode. In the z direction, the period of the potential is $d = 5.3 \mu\text{m}$. A sequence of about 30 wells is populated by condensates containing about $N = 1200\text{--}1300$ molecules each.

To observe the interference, the trapping potential is turned off nearly instantaneously at $t = 0$. The condensates start to expand and interfere in free space. Dynamics in the z direction is most notable, while the expansion in the orthogonal directions is slow and unimportant here.

If the initial state were a BEC with identical phases φ_j , the evolution would show the Talbot effect: The initial periodic density distribution would reappear at the integer multiples of the Talbot time $T_d = Md^2/\pi\hbar = 1.693 \text{ ms}$, where M is the molecular boson mass.

The observed interference, as shown in Figs. 2(b–e), differs from the Talbot effect dramatically. At $t = T_d/2$ the period of the interference fringes equals to the initial one in agreement with the temporal Talbot effect. At $t = T_d$, however, the prime spatial period is $2d$, which is twice larger than the biggest period possible within the Talbot effect. Snapshots taken after larger evolution time also show that the density modulation is periodic with the period growing linearly with time. In particular, the period is $4d$ at $t = 2T_d$ and $8d$ at $t = 4T_d$ as seen in figure 2(c) and figure 2(d) respectively. The presence of spatial order and increase in periodicity are also seen in the Fourier transforms of the density distribution along z . We display the respective Fourier transforms in Figs. 2(a')–(d'). The increase of the spatial periodicity is seen as the peaks at the fractional spatial frequencies.

We interpret the observation as the interference of molecular BECs whose phases φ_j are random relative to each other. The relative phases of the BECs establish due to the competition between the tunneling, which tends to lock the phases and dephasing, which may happen either due to quantum fluctuations or the temperature.

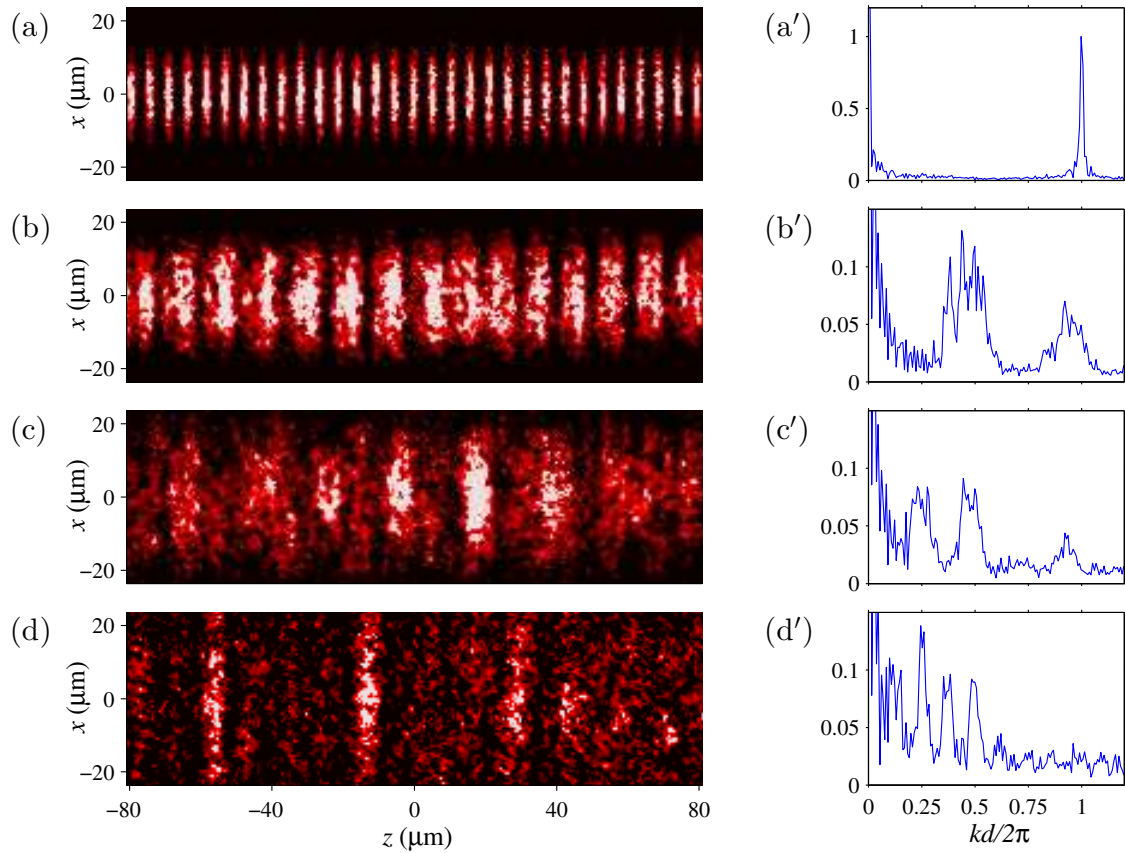


Figure 2. The interference of BECs prepared at $t = 0$ with random phases relative to each other. (a)–(d): Images taken at $t = 0$, $t = T_d$, $t = 2T_d$, and $t = 4T_d$ respectively. In each image one may see periodic density distribution. (a')–(d') are Fourier transforms of density distribution along z for the respective times. Increase of the spatial period is seen as peaks at fractional spatial frequencies.

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