Quantum Electronics **47** (9) 803–805 (2017)

https://doi.org/10.1070/QEL16466

Spatial order in interference of a chain of Bose condensates with random phases

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Abstract. **We have observed the interference of a long chain of Bose condensates prepared at the initial time moment in antinodes of a standing electromagnetic wave. The initial distribution of the condensate density in the system under consideration is periodic while the condensate phases can be different. Then the standing wave is quickly turned off, and the condensates start to expand and interfere. A spatial order of the interference fringes is observed with a period being substantially different from the period arising in the case of the Talbot effect.**

Keywords: *laser cooling, low temperatures, Bose–Einstein condensation, interference of matter waves, Talbot effect.*

Several areas of physics and related disciplines have been further developed thanks to the techniques of laser cooling and trapping of matter [1, 2]. The most accurate and stable frequency and time standards have been established on the basis of ultracold atomic gases [3, 4]. In a gas of ultracold atoms excited up to Rydberg states [5, 6], algorithms of quantum informatics can be implemented [7]. The interference of de Broglie waves enables high-accuracy measurements of angular and linear accelerations, including free fall acceleration [8]. Gyroscopes on ultracold atoms are being developed [9, 10].

Laser cooling is widely used in fundamental research, primarily to observe collective quantum effects [11, 12]. Unlike experiments with a solid, there are no uncontrolled impurities in the atomic experiment, which allows one to uniquely identify the cause of the effect observed. And in contrast to nuclear physics, there are much greater opportunities to observe the system under study. In addition, in atomic experiments, it is possible to adjust the cross section and the sign of interparticle interactions, which also allow for gaining a correspondence between the experiment and the model.

In experiments with ultracold gases of Bose and Fermi atoms, a number of effects have been first observed, the mathematical models of which form the basis of quantum physics, for example, Fermi pressure [13] and Bose condensation [14]. To date, a large number of experiments with Bose condensates have been conducted [11, 15, 16]. The condensation of atoms and molecules was studied in [17]. The interference of Bose condensates was observed in [18]. Hereafter, the interference was used to study the correlation properties in a condensation process [19]. For a Bose condensate, on the wave function of which a periodic spatial modulation is imposed, the quantum Talbot effect [20] was observed – an evolution, in the course of which, at certain time moments the wave function reproduces its original form.

In this work we have investigated experimentally a generalisation of the interference problem for a long chain of Bose condensates. The initial condition is chosen to be less stringent than that required for the realisation of the Talbot effect: the preparation method provides a periodic density distribution in the chain of condensates (Fig. 1), with an arbitrary phase relationship between the condensates being allowed. It is found that the evolution of such a chain of condensates is qualitatively different from the Talbot effect – in the course of evolution a quasi-periodic spatial density distribution arises, the period of which increases with time and may significantly exceed the period of initial modulation.

In the experiment, a chain of Bose condensates of molecules prepared in a one-dimensional optical lattice has been used (Fig. 1a). The experimental setup is described in [21, 22]. The role of bosons is played by Li_2 molecules in a long-lived excited vibrational state. Each molecule consists of two Fermi atoms ^6Li. The optical lattice is formed by two opposing

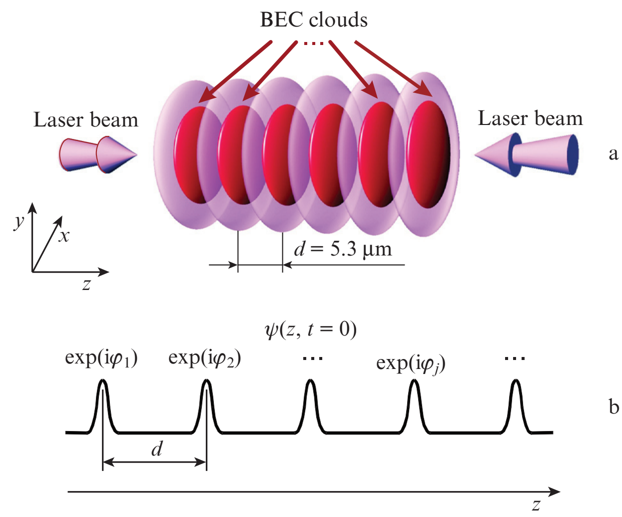

Figure 1. (a) Trapping of Bose–Einstein condensates (BECs) of Li_2 molecules in the antinodes of a standing electromagnetic wave (the condensates are shown in dark grey colour, the radiation intensity distribution is light grey), and (b) wave function of condensates immediately before switching off the lattice potential (t = 0). The density [$|\psi(z, t = 0)|^2$] of condensates is a periodic function, while the phases φ_j of condensates can be different.

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Received 7 July 2017
Kvantovaya Elektronika **47** (9) 803–805 (2017)
Translated by M.A. Monastyrskiy

beams of laser radiation with a wavelength of 10.6 μm and identical polarisations. The lattice potential is

$$V(x,y,z) = sE_{\rm rec}\left\{1 - \exp\left[-\frac{M\omega_\perp^2(x^2+y^2)}{2sE_{\rm rec}}\right]\cos^2 k_{\rm las}z\right\}, \quad (1)$$

where $\omega_\perp$ is the frequency of the potential in the xy plane; s is the dimensionless depth of the potential; $E_{\rm rec} = \hbar^2 k_{\rm las}^2/(2M)$ is the recoil energy; M is the mass of the Li_2 molecule; and $k_{\rm las} \equiv 2\pi/10.6$ μm. The radiation intensity maxima serve as the potential minima. The molecules are held along the x and y axes due to the Gaussian profile of the radiation mode. In the z-axis direction, the period of the potential d is 5.3 μm. Approximately 30 central cells contain $N = 1200-1300$ molecules each. The preparation of condensate molecules takes about 18 s and starts with the laser trapping and cooling of Fermi atoms ^{6}Li [22, 23]. The atomic gas is first collected and cooled in a magneto-optical trap. Then this trap is turned off and the gas is held by the optical lattice. Further cooling occurs using the evaporation technique [22, 23]. The atomic gas consists of a mixture of an equal number of atoms in the states $|1\rangle$ and $|2\rangle$, which, in the limit of the zero magnetic field, correspond to the states $|F = 1/2, M_F = 1/2\rangle$, and $|F = 1/2, M_F = -1/2\rangle$. To accelerate the evaporation, the cross section of s-collisions between atoms in the states $|1\rangle$ and $|2\rangle$ is increased by imposing a magnetic field corresponding to the boson side of the Fano–Feshbach resonance [24] with a centre at $B = 832$ G. In this case, it is energetically favourable for the atoms to populate a shallow bound state. At the final stage of cooling, almost all the atoms turn out combined into the boson molecules–dimers. It is known that such molecules can form a Bose condensate [17].

The image of the condensates obtained is shown in Fig. 2a. For them to be recorded, the gas is illuminated by a pulse of monochromatic radiation propagating in the y-axis direction, with a frequency resonant to the electro-dipole transition frequency in the atom with a wavelength of 671 nm. Since the binding energy of atoms in a molecule is small, the light scattering cross section for these atoms is almost the same as for unbound atoms. The pulse duration is 4 μs, which is much less than the characteristic times for the interference of the de Broglie waves of molecules. A shadow from the clouds of molecules is projected onto a charge-coupled device, which enables to reconstruct the gas density distribution integrated along the y axis [22] and obtain the number of molecules. The image recording destroys the quantum system, which is prepared anew for repeated measurements.

At the time moment $t = 0$, the lattice potential (1) is turned off almost instantaneously. As a result, the condensates start to expand in free space, overlap and interfere. The most noticeable dynamics takes place in the z-axis direction, while the spread in the orthogonal directions x and y is much slower and in this case is of no significance. If the condensates had identical phases φ_j, then the Talbot effect could have been

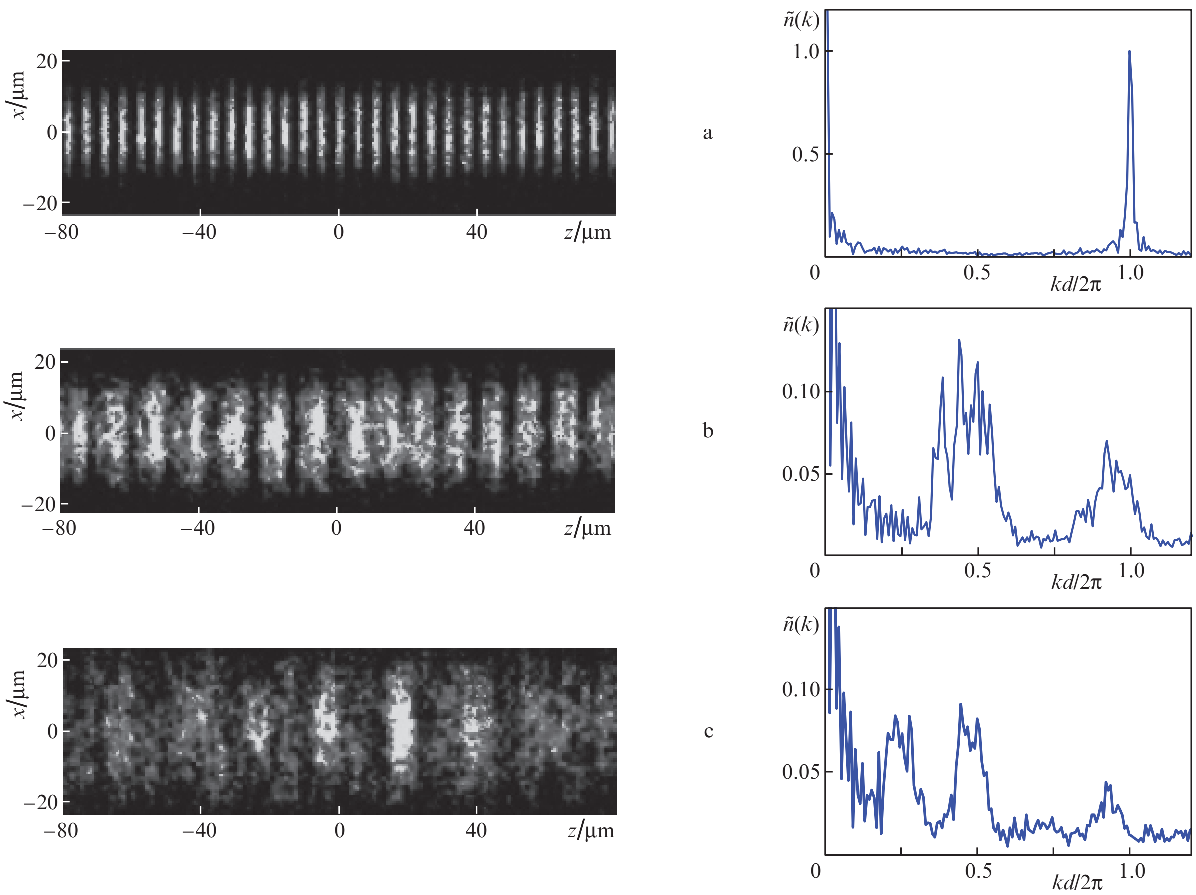

Figure 2. Images of the Bose condensates trapped in an optical lattice (1) and the corresponding Fourier transforms $\tilde{n}(k) = \int|\psi(z,t)|^2\exp(-ikz)dz$ of the condensate density distributions along the z axis at the time moments t = (a) 0, (b) T_d and (c) $2T_d$. The presence of a spatial period at each time moment can be seen from the peaks in the Fourier transforms.

observed in the course of evolution: the wave function of the condensates $\psi(z, t)$ would have returned to its initial form $\psi(z, t = 0)$ at the time moments being multiples to the Talbot time $T_d = Md^2/(\pi\hbar) = 1.69$ ms.

The images of the interfering condensates are shown in Figs 2b and 2c. We should note the following. Firstly, the presence of more or less direct interference fringes indicates the validity of the initial assertion that the Bose condensates have been prepared. In the case of an uncondensed gas, the density distribution of the condensates would have been much more homogeneous. Secondly, the density distribution observed in the course of interference differs qualitatively from the distribution for the Talbot effect. In particular, at the time moment $t = T_d$, the density distribution along the z axis is periodic with a period of $2d$, which can be seen from the presence of a corresponding peak in the Fourier transform of the density distribution. The period $2d$ is twice as long as the maximum period allowable in the frame of the Talbot effect. The image in Fig. 2c obtained at a later time moment $t = 2T_d$ also shows a periodic distribution, but with an even greater period $4d$.

The images in Figs 2b and 2c can be interpreted as a result of interference of the condensates having initially essentially uncorrelated phases. Consequently, the wave function of condensates can be approximated at $t = 0$ as a sum:

$$\psi(z, t = 0) \propto \sum_{j=1}^{K} \exp\left[-\frac{(z - jd)^2}{4\sigma^2}\right] \exp(\mathrm{i}\varphi_j), \qquad (2)$$

where K is the number of condensates, and the width σ of each of them satisfies the overlap absence condition: $\sigma \ll d$. Since each condensate has a certain, albeit random phase, the appearance of any interference pattern is expected. At the same time, the appearance of a spatially periodic density distribution at each time moment is of interest. The results of numerical calculation of the evolution of the wave function (2) in free space qualitatively coincide with the experimental data. In particular, in the calculated density distribution, spatial periodicity and an increase in the period with time are observed.

Note that the interference of the chains of condensates, whose phases have different degrees of correlation with each other, has been previously studied in Refs [25, 26]. In contrast to the case considered in the present paper, the interference occurred in the Fraunhofer diffraction zone. A periodicity has been observed in the distribution of the interference fringes. However, the spatial period of the fringes was the same for both correlated and uncorrelated condensate phases. Thus, the difference in the spatial periods of the interference fringes we have considered represents a peculiarity of the interference in the Fresnel diffraction zone, to which the Talbot effect also refers.

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