Moiré Pattern of Interference Dislocations and Superfluidity in Condensate of Indirect Excitons

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Abstract: We present a new mechanism, the moiré effect, which leads to the appearance of dislocations in interference patterns. Remote interference dislocations in condensate of indirect excitons originate from the moiré effect and evidence exciton superfluidity. © 2021 The Author(s)

Dislocations (forks) in interference patterns is a ubiquitous phenomenon in quantum systems. This phenomenon has been associated with vortices. Dislocations in interference patterns were reported for optical vortices [1], vortices in atom condensates [2], polariton vortices [3], and magnon vortices [4].

We present a new mechanism, which leads to the appearance of dislocations in interference patterns. This mechanism is uncovered by exploring a quantum system of indirect excitons (IXs). IXs are bound pairs of electrons and holes, which are confined in separated layers in coupled quantum well (CQW) heterostructures. IXs have long lifetimes within which they can cool below the temperature of quantum degeneracy and form a Bose-Einstein condensate [5]. The IX condensation is detected by the measurement of IX spontaneous coherence [6].

The theory predicts superfluidity in IX condensates [5] that can enable ballistic IX propagation over macroscopic distances and can lead to long-scale interference patterns. In this work, we analyze interference dislocations in condensate of IXs. We show how various exciton vortices and skyrmions should appear in the interference experiments and show that isolated dislocations observed in interference patterns are not associated with vortices or skyrmions. We show that the observed interference dislocations originate from the moiré effect in the combined interference patterns of condensate matter waves ballistically propagating over macroscopic distances. The moiré effect is a new mechanism for dislocations in interference patterns. The ballistic IX propagation over macroscopic distances is the evidence for IX condensate superfluidity.

Localized bright spot (LBS) sources are stable and well-defined sources of cold IXs [6], we use them here for exploring phenomena in propagating condensate matter waves. The interference images are measured by shift-interferometry. As a result of IX recombination, IXs transform to photons. These photons go through the Mach-Zehnder interferometer. Each of the two interferometer arms forms an image of the IX emission on CCD detector. These two images are shifted relative to each other in x direction so that the measured interference pattern is produced by the interference between the emission of IXs separated by the shift δx in CQW plane. The measurements are performed at temperatures $T \geq 100$ mK in an optical dilution refrigerator.

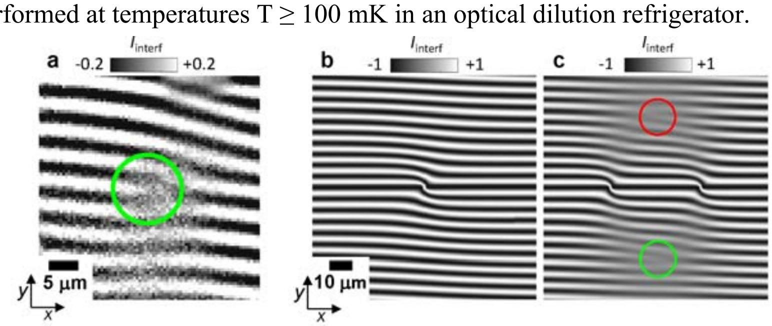

Figure 1. (a) Measured interference pattern $I_{interf}(x,y)$. (b,c) Simulated $I_{interf}(x,y)$ for a radial IX condensate matter wave propagating from a source in the center (a) and for two radial IX condensate matter waves propagating from two sources separated along **x** (b). The interference dislocations marked by green and red circles originate from the moiré effect in the combined interference patterns of the IX condensate matter waves.

Figure 1a presents a dislocation in the interference pattern. Our simulations show that a vortex, polarization vortex, or half-vortex should lead to the appearance of a pair of left- and right- dislocations separated by δx and that a skyrmion or half-skyrmions should not lead to the appearance of a dislocation. In contrast to the vortex or skyrmion interference patterns, the experiment (Fig. 1a) detects an isolated interference dislocation, that is, a dislocation separated from other dislocations by distances much larger than δx. The origin of the isolated interference dislocations separated from IX sources by macroscopic distances is outlined below.

The interference pattern of two radial IX condensate matter waves produced by two sources reproduce the isolated dislocations observed in the experiment (Fig. 1c). The interference dislocations originate from the moiré effect in the combined interference patterns of condensate matter waves. The radial condensate matter waves propagating from source 1 and from source 2 create similar interference patterns (Fig. 1b) shifted relative to each other by the separation between the sources. Combining these two interference patterns forms a moiré pattern with dislocations.

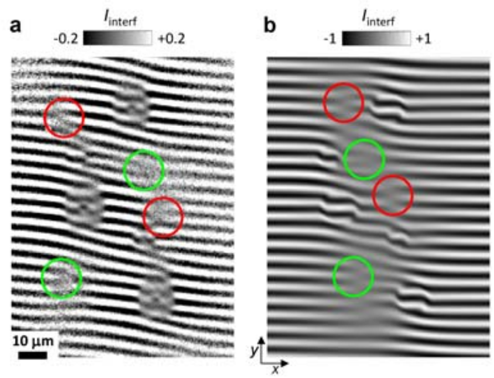

Figure 2. (a) Measured $I_{interf}(x,y)$ for IXs in the region of five LBS sources. The right- and left-oriented interference dislocations are marked by red and green circles. (b) Simulated $I_{interf}(x, y)$ for five radial IX condensate matter waves ballistically propagating from five sources positioned at the locations of LBS sources. The simulations (b) reproduce the interference dislocations observed in the experiment (a).

In the experimental system, there are several LBS sources of IXs (Fig. 2a). Three strong sources are clearly seen due to the pronounced phase domains at the source locations. These phase domains are associated with the Pancharatnam-Berry phase and are described in [7]. Two weaker sources are also seen in Fig. 2a. The right- and left-interference dislocations are marked by red and green circles. All sources participate in the formation of these dislocations. A stronger contribution to the upper (lower) pair of right- and left- dislocations is given by the two upper (lower) strong sources, so these pairs of dislocations are mainly produced by the pairs of sources as in Fig. 1c.

Simulated interference pattern for five radial IX condensate matter waves ballistically propagating from these five sources is presented in Fig. 2b. The simulations within the moiré-effect model (Fig. 2b) reproduce the interference dislocations observed in the experiment (Fig. 2a).

The interference dislocations are formed by the IX condensate matter waves ballistically propagating from the IX sources to the locations of interference dislocations over distances reaching ~30 microns. The long-range ballistic IX propagation over these macroscopic distances shows that IXs propagate without scattering over dramatically long times, orders of magnitude longer than in classical exciton gas, and, therefore, is the evidence for IX condensate superfluidity. The interference dislocations disappear in a classical exciton gas at high temperatures. This is consistent with the requirement of long-range ballistic IX propagation, which is provided by superfluidity.

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