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Kinematics and rotation of a vortex lattice in a polariton fluid

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Summary. — We study the kinematic properties of a rotating vortex lattice imprinted on a freely expanding polariton quantum fluid. Thanks to the optical component of polaritons, we can directly measure the phase and modulus of the complex-valued macroscopic wavefunction, and extract the velocity and angular momentum profiles across the condensate. These are in agreement with quantisation prescription, although the non-uniform and unsteady background density profile may induce corrections to the vortex trajectories, and result into fractional orbital angular momentum per particle.

1. – Introduction

In the last decades, a rich research activity has emerged about the dynamics of phase singularities in light fields, giving rise to the modern field of singular optics [1]. When light propagates in a nonlinear medium, the vortex dynamics is often described in terms of quantum fluids of light, based on the well-known analogy between quantum gases, nonlinear optics and fluid dynamics [2]. Exciton-polaritons are a paradigmatic example of quantum fluids of light, particularly interesting for their intrinsic out-of-equilibrium nature and significant optical nonlinearities [3, 4].

Exciton-polaritons (polaritons for short) are bosonic quasi-particles which result from the strong coupling between light (photons) and matter (excitons) in semiconductor optical microcavities with embedded quantum wells [5, 6]. Interestingly, the polariton effective mass is very small (about 10^{-5} m_e) and, depending on the semiconductor material properties, condensation can take place at high critical temperatures, over a wide range of values limited only by the ionization of the exciton (generally 10–300 K) [7-9]. The non-conservative character of the system is due to the unavoidable radiative decay of the optical microcavity and, in most cases, the dynamics is well described by a generalized

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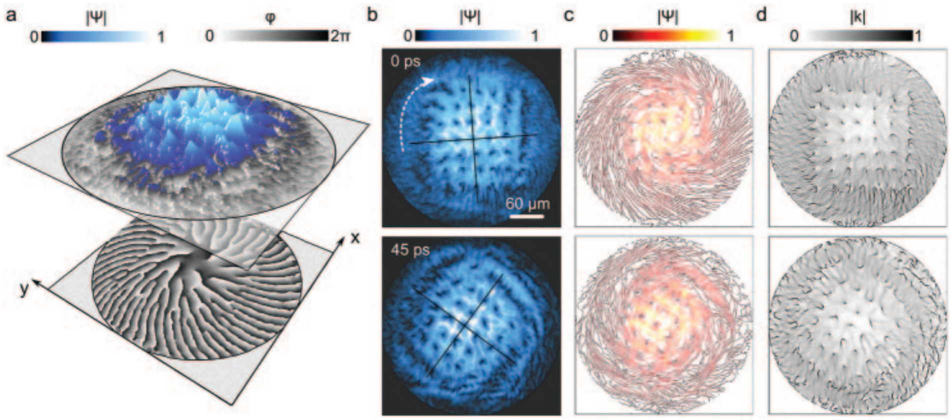

Fig. 1. – Rotating polariton lattice of $n^2 = 49$ equal charge vortices. (a) The macroscopic wave function amplitude field $\psi(\mathbf{x})$ on top of the corresponding phase field $\varphi(\mathbf{x})$, showing the singularity lattice. (b) Normalized amplitude of $\psi(\mathbf{x}, t)$ at two different times, showing the rigid-like rotation of the system. (c), (d) Direction streamlines and normalized intensity maps of the momentum field, underlying the dynamics.

2D Gross-Pitaevskii (GP) equation, where the driven-dissipative character of polaritons is suitably taken into account [10].

Recently, we investigated the spatial and temporal properties of regular lattices of $n \times n$ quantised vortices in untrapped polariton fluid [11], which rotate and simultaneously expand. In this paper, we focus on the kinematic properties of the vortex lattice in terms of the spatial profile of momentum and orbital angular momentum, highlighting general features common to any planar, or quasi-planar superfluid, and to other singular optics configurations.

2. – Vortex lattices in polariton condensates

We use a semiconductor planar microcavity with 12 GaAs quantum wells sandwiched between two distributed Bragg reflectors with high quality factor ($Q = 10000$). The exciton-polariton condensate inherits the phase profile from the suitably modulated laser resonant excitation. Once the laser pulse is over, the polariton condensate, showing the imprinted regular lattice of vortices, is free to rotate and expand. Details of the experiment can be found in the Supplementary Information of [11]. In the condensed state, the polariton fluid is described by a macroscopic wavefunction $\psi(\mathbf{x}, t) = \sqrt{N(\mathbf{x}, t)} e^{i\varphi(\mathbf{x}, t)}$ which obeys the GP equations. In fig. 1, in the left panel we plot a snapshot of the spatial distribution of the (square root) density $|\psi(\mathbf{x})|$ and phase $\varphi(\mathbf{x})$ of the polariton fluid in the 2D plane of the microcavity, obtained by means of the digital off-axis holography technique [12]. The density pattern is clearly not uniform, being the result of the initial, centered Gaussian profile of the laser beam shined onto a spatial light modulator which is mandated to shape the vortex lattice phase pattern [11]. Each vortex core, being a singularity of the phase and a divergence of the transverse momentum, is also associated to a zero of the density. We emphasize that such a 2D initial state is necessarily set into a rotational motion, with initial azimuthal velocities due to the vortex pattern itself. As time elapses, in the absence of a trap, both the density and the contained vortex cores move outward, never reaching a steady profile. The observed expansion is hence mainly the result of the initial tangential velocities remaining basically constant([1]), but with asymptotically larger centrifugal projection due to the renewed positions. Hence, fig. 1(b) shows that a quasi-rigid rotation appears over a time span of few tens of ps. In fig. 1(c),(d), we also show the momentum maps, $\propto \mathbf{k}(\mathbf{x}) = \boldsymbol{\nabla}\varphi(\mathbf{x})$, plotting both its direction and intensity. Thanks to the phase and momentum maps, we observe that each unit of the lattice contributes to the build up of azimuthal momenta and velocities which scale (approximately) linear with the radial distance from the lattice center. Moreover, the lattices shape is preserved, thanks to the radial linear scaling of the initially imprinted velocities, which is the same associated to a rigid rotation. To gain quantitative insight, we can track individual vortex movements and use their positions as a measure of the dynamical evolution, for a time window of about 80 picoseconds, in a very good agreement with this phase gradient inferred velocity.

The Feynman-Onsager relation [13] between the angular rotation frequency Ω and the vortex density $\propto 1/d^2$, prescribes at any instant

$$\Omega = \frac{h}{2m}\frac{1}{d^2}, \tag{1a}$$

where d is the inter-vortex separation. In [11], we showed that in our experiments such relation is weakly verified, in the sense that a small but measurable deviation is present. We explained such deviation in terms of a Magnus-like effect, *i.e.*, a transverse velocity component, in the movement of the vortex cores only, induced by the radial density gradients in the polariton fluid's bell-shape envelope.

As it is well known, the Feynman-Onsager relation is based on the hypothesis that the condensate rotates in a rigid-body movement, such that the fluid, irrotational for simply connected regions, effectively appears as rotational in a coarse grained picture. As a result, in the lattice region, we can define an azimuthal velocity $v = (\Omega \times \mathbf{r}) \cdot \hat{\mathbf{e}}_\theta$. Such an approximation can be appreciated in fig. 2, where we extract from the phase map the azimuthal momentum $k_\theta(r)$ as a function of the radial distance from the condensate center. Apart from the diverging value assumed in the core of the central vortex, $k_\theta(r)$ builds up in a coarsely linear way with r, assuming locally the hyperbolic dependence matched to the circulation of an increasing number of vortices. The quantised nature of vorticity in the condensate unambiguously manifests in the radial profile of the associated orbital angular momentum (OAM), here measured as $\sim k_\theta(r)r$ (or, in other terms, as the circulation of phase). Once the edge of the lattice is achieved, the OAM remains quantized to the total number of vortices (here $n^2 = 49$) from there on. As for the azimuthal momentum, it starts to decrease as n^2/r, as for an irrotational fluid with all the vortices in the center.

In summary, the possibility of accessing both the density and phase maps in a polariton fluid allows appreciating the features of combined rotational and irrotational motions in different regions of the same experiments, as well as highlighting the typical quantized behavior of the OAM build up. Note that because of the presence of a great amount of polariton particles in the lattice interior (see the radial particle number profile in fig. 2), the total OAM per particle —weighted with the mass radial distribution— can be fractional, and smaller than the total number of vortices in the condensate. This conveys

([1]) In case of a nonlinear system, the expansion is initially accelerated by particle repulsion.

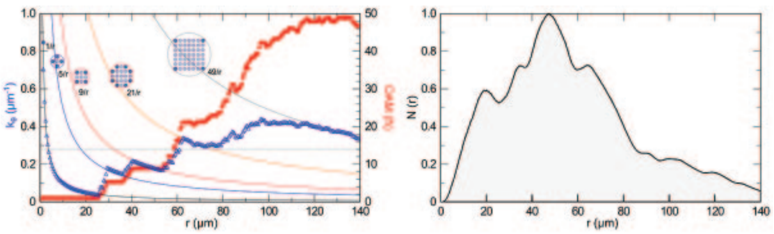

Fig. 2. – (left panel) The radial distributions of the azimuthal momentum (blue triangles), the associated orbital angular momentum (OAM) (red circles). (right panel) The number density radial profile N(r) (grey shaded area). All retrieved from the experiment at initial time. The azimuthal momentum k_θ is spatially averaged (along any circle, without weighting with the density); the OAM is here the phase circulation, obtained by multiplying k_θ by 2π the radius. When these two quantities or the density are uniform on a circle, they assume the meaning of momentum and OAM per particle. The distributions help to understand why the total OAM per particle is intermediate (OAM = 14) wrt the vortex charge ($n^2 = 49$). The inset schemes in the left panel visualize the newly encircled vortices when progressively increasing the radius, with the associated hyperbolic line for k_θ also associated to the quantized steps in the OAM build up.

the idea that, despite the fact that each phase singularity can exert a torque in its close vicinity, there is no direct association between the number of vortices and the integrated OAM for general beams [14] (a preserved association when all the phase singularities are on-axis).

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