The scissors oscillation of a quasi two-dimensional Bose gas as a local signature of superfluidity

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Abstract. We test the superfluid character of a two-dimensional Bose gas confined in an anisotropic harmonic trap through the frequency of the scissors mode. We show that a local analysis of this frequency allows to evidence the boundary between a superfluid phase at the centre of the cloud and a thermal phase at the edge. The location of this boundary agrees well with the prediction of the Berezinskii-Kosterlitz-Thouless theory within local density approximation.

Superfluidity is an intriguing property of certain quantum fluids, which is characterized by a few manifestations in its dynamics: absence of viscosity, existence of a critical velocity for the appearance of excitations, vanishing moment of inertia, hydrodynamic behavior including irrotational flow, quantum vortices and collective oscillations. Widely studied in the context of liquid helium, it has been extended to three-dimensional quantum degenerate weakly interacting Bose gases which appear to present a superfluid character as Bose-Einstein condensation (BEC) is reached.

The case of two-dimensional quantum gases is very different in this respect. In homogeneous gases, BEC is absent while a superfluid transition still occurs at low temperature when local phase fluctuations are reduced by vortex-antivortex pairing, as described by Berezinskii, Kosterlitz and Thouless (BKT) [1, 2]. Superfluidity then exists even in the absence of long range order. In trapped Bose gases, BEC is recovered but the BKT superfluidity mechanism still holds and is responsible for the superfluid character of the sample. As the density is inhomogeneous in a trapped gas, the central core is expected to present a superfluid dynamics while the outer region of the sample is still normal. At equilibrium at a given temperature, the gas properties (density, chemical potential) can be defined locally, which is known as the local density approximation (LDA). The criterion for the BKT transition could then be applied locally, giving rise to the existence of a boundary in the sample between a normal component and a superfluid component.

However, as explained above, superfluidity is a dynamical property and should be tested in a dynamics experiment. In particular, the scissors mode, which is a collective mode describing the oscillation of an anisotropic superfluid around one of the trap axes [3], is characteristic of the superfluid behavior of a dilute gas, and has already been used in the past to identify the superfluid character of a three-dimensional Bose gas [4]. In a recent experiment we have used the

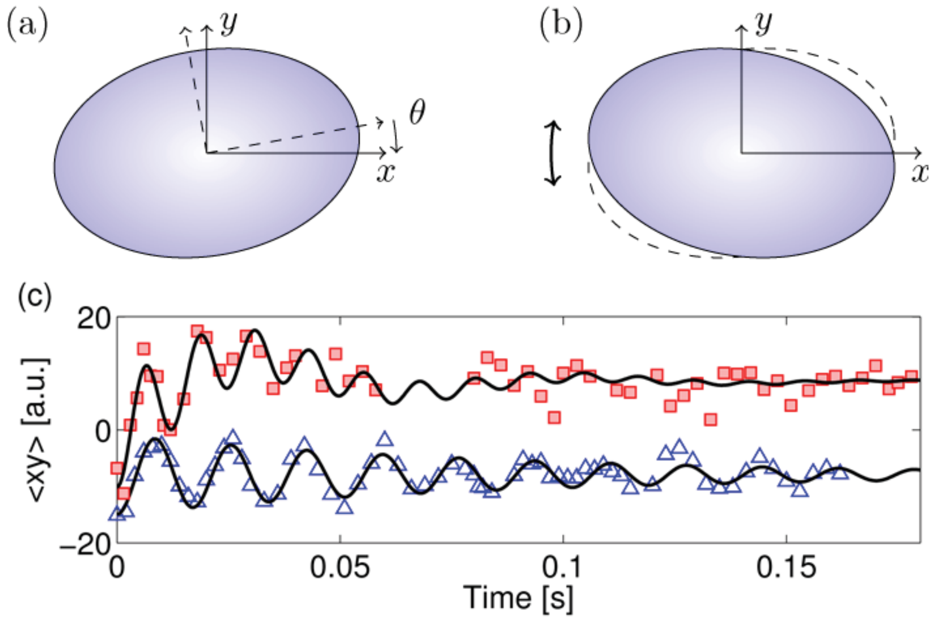

Figure 1. (color online) Excitation of the scissors mode: (a) the trap axes are suddenly rotated by an angle θ and (b) the gas starts oscillating around the new long trap axis. (c) Typical evolution of the observable $\langle xy \rangle$ (average value of xy), which is characteristic of the scissors mode. Red squares: thermal gas, two damped frequencies are present but no superfluid mode; blue triangles: superfluid oscillation of a well defined scissors mode.

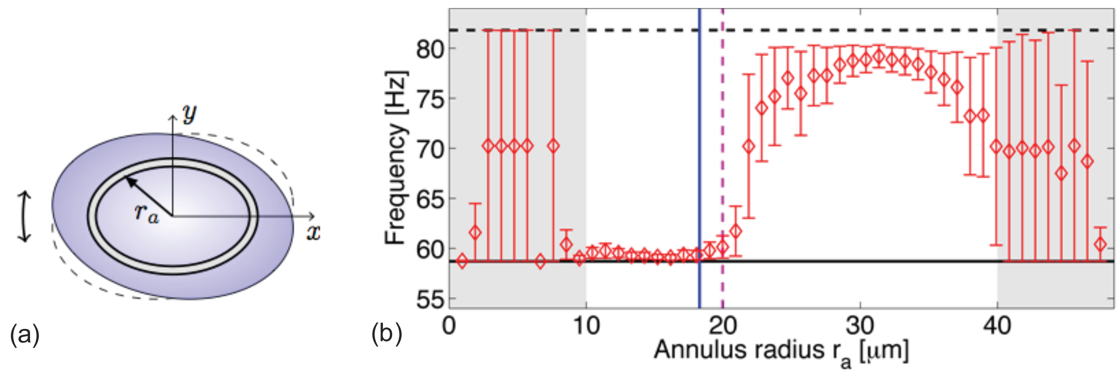

Figure 2. (color online) (a) Region of local average analysis: the average $\langle xy \rangle$ is computed in a thin annulus of radius r_a. (b) Frequency of the scissors mode as a function of the analysis annulus radius r_a. A transition from the superfluid frequency near the center (small r_a) to a normal frequency near the edges (large r_a) is clearly visible. The blue vertical line corresponds to the expected BKT threshold computed for a homogeneous gas within the LDA.

scissors mode to characterize the superfluid nature of a trapped two-dimensional Bose gas, for various values of the temperature and chemical potential at the center [5]. Some of the samples are purely superfluid and evolve at the scissors frequency, others are purely normal and present beat notes between the two trap frequencies (figure 1). On the other hand, we also observe samples which present a clear bimodal behavior. Thanks to a local average analysis of the gas oscillation frequency (figure 2(a)), we are able to isolate the superfluid phase from the normal phase in these samples. It is evidenced by a sudden change in the scissors mode frequency as a function of the distance to its center, located at a well-determined boundary corresponding to the normal to superfluid threshold (see figure 2(b)).

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