Imaging the collective modes of a two-dimensional Bose gas

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Quantum gases are fascinating systems for the investigation of the properties of quantum matter. They can be produced nowadays in a wide variety of geometries. Their properties, including volume, temperature and interactions between atoms, can be controlled with external optical, magnetic or radio-frequency fields. For the last ten years, dramatic progress has been made in the investigation of low dimensional quantum gases. When quantum gases are confined to one or two dimensions, the role of quantum correlations is strongly enhanced and the physics changes qualitatively [1]. Specifically, a homogeneous bosonic gas restricted to two dimensions undergoes a Berezinskii-Kosterlitz-Thouless (BKT) transition to a superfluid below a critical temperature. After important success in the characterisation of equilibrium properties of two-dimensional quantum gases (in particular in the ENS and Chicago groups), the dynamical properties start to be unveiled.

The study of the excitation modes of a quantum gas is a way to characterise the dynamical properties. In particular, the low energy excitations of a quantum gas trapped in an anisotropic harmonic potential are collective modes. They can be excited by inducing a sudden change in the trap parameters. The monopole, or breathing mode, is a compression mode. For this reason, it gives access to the equation of state at zero temperature of the gas, linking its chemical potential to its density. We have shown recently that it can unveil dimensionality effects in a quasi two-dimensional Bose gas [2,3]. On the other hand, the scissors mode can be used to characterize the superfluid phase [4].

Here, we present the first direct imaging of the low energy collective modes excited simultaneously in a two-dimensional anisotropic trapped bosonic quantum gas. The modes can be identified with the first excitations deduced from the Bogolubov theory for a trapped Bose gas: the two dipole modes (or centre of mass oscillations), the scissors mode, the monopole-like mode (or breathing mode) and the quadrupole-like mode, see Fig. 1. This result is allowed by the use of a statistical analysis of a series of absorption pictures, Principal Component Analysis (PCA), which gives access directly to the collective modes, their shape and frequencies, without any a priori assumption or fitting function relying e.g. on the Thomas-Fermi approximation [5].

The observation of low energy Bogolubov excitations is performed in a quantum degenerate gas of rubidium 87 atoms confined to two dimensions in a radio-frequency (rf) dressed magnetic quadrupole trap [6]. We can dynamically control the precise trap shape by varying the magnetic or rf fields, which results in selective excitations of the gas normal modes. We measure the gas properties by performing in-situ absorption imaging along the strongly trapped vertical direction. The gases we consider are in the quasi two-dimensional regime: the excitations along the imaging axis are frozen and the dynamics occurs only in the horizontal plane. We use the dipolar mode – which is not expected to be damped in an harmonic trap – to characterise the trap geometry and demonstrate its harmonic character and its smoothness.
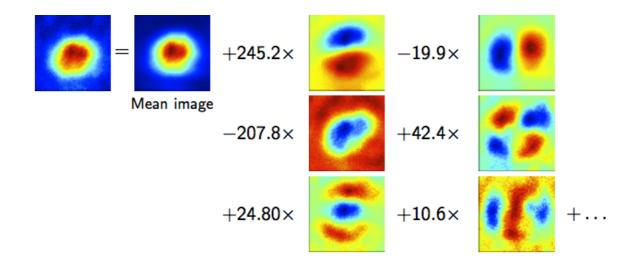
Figure 1 : Decomposition of the measured atomic density of a single image onto the first principal components as computed from a series of 133 images [5]. The main contributions on top of the mean image arise from the two dipole modes, the fluctuations in the overall atom number, the scissors mode, the monopole-like mode and the quadrupole-like mode.

We apply PCA to the study of the cloud dynamics after a sudden change of the trap parameters. We record a series of 133 images of the resulting dynamics after various holding times in the trap. PCA allows to properly identify the first Bogolubov excitations, which appear as the principal components, see Figure 1. The projection of an image in the series onto a given principal component evolves in time at the mode frequency. Thanks to this technique we identified the two dipole modes, evolving at the trap frequencies, the monopole-like and quadrupole-like modes, as well as the scissors mode. This last mode presents three characteristic frequencies, one corresponding to true scissors mode of the superfluid fraction while the two others are combinations of the oscillation frequencies and can be attributed to the thermal fraction. These results pave the way of the study of the superfluid transition in a two-dimensional Bose gas.

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