ATOMIC PHYSICS

Cold gases venture into Flatland

Vortex structures have revealed a lot about the nature of three-dimensional Bose–Einstein condensates. They play an even bigger part in two-dimensional cold atomic gases and drive a fundamentally different phase transition.

Keith Burnett
is at the Department of Physics and Astronomy, University of Sheffield, Hicks Building, Hounsfield Road, Sheffield S3 7RH, UK.
e-mail: Keith.Burnett@Sheffield.ac.uk

Vortices are all around us. They are seen as water drains away from a sink or as a 'twister' in a storm. They are seen in the smoke rings that used to be blown by experienced smokers. Because of their fascinating form, vortices are commonly referred to in almost mystical terms. They enthralled my nineteenth-century predecessor at Sheffield University — William Hicks — who studied the ways in which atoms could be made out of vortices in the substance of the 'ether'[1]. It was William Thomson's (later Lord Kelvin) idea that vortices were permanent objects in the ether that could make up stable components, that is, atoms of the material world.

In modern times, vortices play a fundamental part in understanding superfluids and superconductors. Their presence enables a superfluid — a fluid that cannot undergo rigid-body-like rotation — to carry angular momentum. The presence of quantized vortices shows that a system is a superfluid, and the production of vortices in rotating trapped condensates was crucial to establishing the superfluidic nature of the atomic Bose–Einstein condensates (BECs)[2].

As reported in *Physical Review Letters*, Peter Krüger and co-workers[3] have taken a step into a new regime. They describe experiments probing the role of vortices in an effectively two-dimensional atomic gas. The role of vortices is different in two dimensions from that seen in three. As this atomic 'Flatland' is cooled to the temperature range at which in three dimensions Bose–Einstein condensation takes place, we see in two dimensions, at first, a 'normal gas' with plenty of vortices moving freely throughout. As the temperature is lowered further, a critical temperature is reached — known as the Berezinskii–Kosterlitz–Thouless (BKT) transition temperature — at which the vortices bind together in pairs. This leads to a rapid increase in the superfluid density of the gas. The appearance of this superfluid without long-range order is quite different from that of a BEC, and relies on the presence of local interactions. Krüger *et al.*[3] observed this transition in a trapped atomic gas for the first time. They also confirmed that the two-dimensional system undergoes a BKT transition, rather than Bose–Einstein condensation.

Mystical beauty. Vortices — seen and studied in so many contexts — offer the key to understanding the behaviour of two-dimensional atomic gases at low temperatures.

The BKT transition was first observed 1978 in liquid-helium films[4]. So what is the point of studying it in evaporatively cooled atoms? The first advantage is the possibility of observing directly the atomic correlation (or coherence) function. This is equivalent to observing the first-order coherence of an optical field. There is no true long-range order in a two-dimensional system. There is, however, another characteristic feature predicted by theory, and that is algebraic decay of the atom–atom coherence[5]. This can be observed directly when two spatially separated quasi-two-dimensional gas clouds — whose shape is reminiscent of that of a pancake — are produced; on release from the optical trap that confines the clouds, the two 'pancakes' overlap and directly reveal an interference pattern that shows the onset of coherence.

Another crucial difference is the ability that we have, in the atomic case, to vary densities and interaction strengths. This is a crucial advantage because the general theory predicts a jump in the superfluid density at the BKT transition, but does not reveal how this will affect actual total density of atoms in the system. The relationship between superfluid density and total density depends on the strength of the interaction between the atoms and can be predicted using numerical simulations of the system. In the experiments using cold gases, the interaction strength can be changed using a so-called Feshbach resonance, enabling a full study of the microscopic BKT superfluid.

We should note that there was a real debate about whether Bose–Einstein condensation or BKT transition would be seen with a trapped two-dimensional gas. The experiments of Krüger and colleagues[3] show results consistent with a BKT transition and inconsistent with Bose–Einstein condensation.

There is a great deal more to be studied in these two-dimensional systems in addition to the issues mentioned above. For example, the ability to increase the interaction strength should enable experimenters to approach the situation where quantum fluctuations are dominant. This takes place when the number of atoms that participate in a vortex is small; in essence, the vortex stops being a classical object. We know that in the case of vortices induced by rotation of a condensed gas, when the number of atoms per vortex is low enough, the vortices 'melt', and we encounter a topologically ordered state related to the fermionic fractional quantum Hall effect[5].

With such exciting opportunities ahead, the experiments of Krüger *et al.* point to a new avenue of research in two-dimensional many-body physics.

References

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