More than 70 years after its first discovery, superfluidity is still challenging researchers to unveil its most subtle aspects [1]. Among its many odd properties, a superfluid is characterized by a zero viscosity, i.e., the ability to flow without apparent friction. Long after the pioneering observations of these effects in liquid helium in the 1930s and 1940s, the development of laser cooling techniques for atomic gases has offered experimentalists a new framework for investigating the fundamental concepts of superfluidity and its not-so-direct relation with Bose-Einstein condensation. Writing in Physical Review Letters, Nigel Cooper and Zoran Hadzibabic from Cambridge University, UK, now propose [2] a novel protocol to experimentally address superfluidity in gases of ultracold atoms independently from condensation. Application of this method to strongly correlated atomic Fermi gases with nontrivial pairing mechanisms [3] will hopefully contribute to our understanding of puzzling condensed matter phenomena such as high-temperature superconductivity.

Soon after the first observations, Fritz London proposed that Bose-Einstein condensation—the phenomenon in which bosons below a transition temperature accumulate into a single one-particle quantum state—might be responsible for superfluidity of liquid helium. Several decades elapsed before London’s hypothesis got a direct experimental verification from the measurement of the momentum distribution by means of neutron scattering experiments [4]: even at the lowest temperatures where the superfluid fraction is almost 100%, the strong correlations between the atoms forming the liquid deplete the population of the Bose-Einstein condensate state to only 10% of the total mass.

The situation is substantially different in dilute ultracold atomic gases. At low temperatures, such gases are in fact almost fully condensed and superfluid, but a conceptual difference still exists between the two properties. Researchers now routinely measure the condensate fraction by looking at the velocity distribution in time-of-flight images, but some conceptual aspects of superfluidity are still awaiting experimental investigation. In contrast to the complex microscopic structure of liquid helium, the simplicity of the theoretical description of dilute atomic gases allows a deep understanding of the basic mechanisms underlying superfluidity phenomena in simple terms.

One of the neatest formulations of the concept of superfluidity involves the response of the fluid to rotation in the so-called “rotating bucket experiment”: while the normal component of the fluid is dragged by the bucket, the superfluid component is almost unaffected by the rotating walls [1]. This idea was first put into practice in 1946 by Andronikashvili using a torsional oscillator and a bulk three-dimensional sample of liquid helium (see Fig. 1, left panel): the appearance of a superfluid is detected by the drop in the moment of inertia [5]. Interesting measurements of the reduced moment of inertia of atomic Bose-Einstein condensates have been performed by looking at the frequency of the so-called scissors mode in an anisotropic trap and at the time evolution of the shape of an expanding condensate after releasing the trap [6].

The definition of superfluid fraction can be formulated in a formal and quantitative way in terms of the response of the fluid to an external vector field [7]. If placed in a rotating trap, neutral atoms behave in fact as if they were subject to a constant magnetic field parallel to the rotation axis; in this picture, the absence of response to rotation is the superfluid analog of the Meissner effect of superconductors in which magnetic fields are excluded from the material. Along these lines, it was soon recognized that the study of the response of the gas to artificial magnetic fields may offer a much wider range of experimental possibilities to investigate superfluidity.

The idea of creating artificial magnetic fields for neu-
The vector potential ttees adiabaticity if the atomic motion is slow enough. The separation between the dark and bright states guarantees a coherent population trapping mechanism. The energy directly to the light field (a so-called "dark" state) via be used to drive the atoms into a state that does not couple along an adiabatic closed contour in real space. In the case of three-level atoms, two coherent laser beams can manipulate Bose-Einstein condensates has been recently verified with the observation of quantized vortices for large enough values of the applied effective magnetic field [9].

The concept of superfluidity is not limited to systems at or close to thermodynamic equilibrium, however. Very recently, experiments on quantum degenerate gases of exciton-polaritons in semiconductor planar microcavities have started exploring many-body physics in a regime where the standard concepts and tools of statistical mechanics cannot be straightforwardly applied. An external pump is in fact needed to compensate losses due to the very short polariton lifetime and the nonequilibrium stationary state is determined by a dynamical balance of pumping and losses [12]; this fact, rather than a hindrance as initially believed, is nowadays leading to interesting new physics. Bose-Einstein condensation of

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polaritons has been demonstrated from the long-range coherence of the emitted light [13], and the superfluidity properties of these nonequilibrium polariton gases are presently attracting a strong interest in both the experimental [14] and the conceptual points of view [15]. To put these investigations on a quantitative level, protocols to directly measure the superfluid fraction independently of condensation will be of extreme utility.

References


About the Author

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Iacopo Carusotto completed his Ph.D. in 2000 at Scuola Normale Superiore in Pisa, Italy, followed by post-doctoral work at Laboratoire Kastler Brossel of École Normale Supérieure in Paris. Since 2003, he has been a researcher at the BEC Center of CNR in Trento, Italy. He has been an associated researcher for CNRS in France and visiting professor at ETH-Zurich. One of his primary scientific interests is superfluidity effects in degenerate gases of atoms and of exciton-polaritons in solids and, more generally, the theory and phenomenology of quantum fields in optical and condensed-matter systems.