Preface

The concept of *quantum fluid*—a fluid whose properties are governed by the laws of quantum mechanics—dates back to 1926, when Madelung introduced the hydrodynamic formulation of the Schrödinger equation. This, along with the prediction of Bose-Einstein condensation (BEC) for a non-interacting gas made by Einstein in 1924, and the discovery of superfluidity in liquid helium, achieved independently by Kapitza and Allen in 1937, can be considered the early milestones of this fashinating field.

Remarkably, though the role of Bose-Einstein condensation in the superfluid behaviour of helium was soon recognized by London in 1938, it took seventy year before its first direct observation. In fact, it was only in 1995 that the groups of Cornell, Weiman, and Ketterle achieved to cool a sample of atomic gases down to temperatures of the orders of few hundreds of nanokelvins, below the critical temperature for BEC. These landmark experiments have produced a tremendous impact in the experimental and theoretical research in the field of quantum fluids. In fact, thanks to the fact that interacting Bose-Einstein condensates (BECs) are genuine superfluids and that they can be controlled and manipulated with high precision, they have made possible to investigate thorougly many of the manifestation of superfluidity, as quantized vortices, absence of viscosity, reduction of the moment of inertia, occurrence of persistent currents, to mention a few.

Very recently, in 2006, following a pioneering proposal by Imamoglou (1996), BEC was observed in a solid state system: polaritons in semiconductor microcavities, which are composite bosons arising from the strong coupling between excitons and photons. Due to their very light mass, several orders of magnitude smaller than the free electron mass, polaritons can exhibit Bose-Einstein condensation at higher temperature and lower densities compared to atomic condensates. On the other hand, polaritons constitute a new type of quantum fluid with specific characteristics coming from its intrinsic dissipative and non-equilibrium nature.

The main objective of this book is to take a snapshot of the state of the art of this fast moving field with a special emphasis on the hot-topics and new trends. Bringing together the contributions of some of the most active specialists of the two areas (atomic and polaritonic quantum fluids), we expect that this work could facilitate the exchanges and the collaborations between these two communities working on subjects with very strong analogies. The book is organized in two distinct parts, preceded by a general introduction; the first part is focussed on polariton quantum fluids and the second one is dedicated to the atomic BEC.

In the introductory chapter, M. Wouters gives an overview of the physics of the Bose-Einstein condensates of ultracold atoms and polaritons underlining their analogies and differences. This chapter reviews the main achievements and discusses the current trends of both fields.

Chapter 2 by N.G. Berloff and J. Keeling deals with the central problem of the universal description for the non-equilibrium polariton condensates. A special attention is paid to the theoretical framework describing the pattern formation in such systems. Different equations characterizing various regimes of the dynamics of exciton-polariton condensates are reviewed: the Gross-Pitaevskii equation which models the weakly interacting condensates at equilibrium, the complex Ginsburg-Landau equation which describes the behaviour of the systems in presence of symmetry-breaking instabilities and finally the complex Swift-Hohenberg equation. The authors also show how these equations can be derived from a generic laser model based on Maxwell-Bloch equations.

In Chap. 3, A. Kavokin develops a general theory for the bosonic spin transport that can be applied to different condensed matter systems like indirect excitons in coupled quantum wells and exciton-polaritons in semiconductor microcavities. The relevance of this approach to the emerging field of Spin-optronics in which the spin currents are carried by neutral bosonic particles is discussed and fascinating perspectives like spin-superfluidity are addressed.

Chapters 4 and 5 are focussed on the theoretical description of the properties of the spinor polariton condensates with a special emphasis on the occurrence of topological excitations in these fluids. In Chap. 4 by Y.G. Rubo, a review of the spin-dependent properties of the multi-component polariton condensates is presented. Special attention is devoted to describe the effect of applied magnetic fields on the polarization properties of the condensate; fractional vortices are discussed and the spin texture of the half-vortices in presence of the longitudinal-transverse splitting is discussed in detail. In Chap. 5, H. Flayac, D.D. Solnyshkov and G. Malpuech first discuss in detail the specific behaviour of a flowing spinor polariton allowing for the generation of a new kind of topological excitations: the oblique half solitons. In the second part of the chapter the authors show that these systems are extremely promising to study exotic entities analogue to the astrophysical black holes and wormholes.

Chapters 6 and 7 deal with experimental studies of hydrodynamics of polariton quantum fluids. In Chap. 6, B. Deveaud, G. Nardin, G. Grosso and Y. Léger describe the behaviour of a flowing polariton quantum fluid perturbed by the interaction with a potential barrier: this experimental configuration is well suited to investigate the onset of quantum turbulence in a quantum fluid. The variations of the phase and density of the fluid are measured with a picosecond resolution allowing for the observation of the nucleation of quantized vortices and the decay of dark solitons into vortex streets. In Chap. 7, D. Ballarini, A. Amo, M. de Giorgi and D. Sanvitto review the first observations of superfluidity in a polariton fluid: the most relevant manifestations of the superfluid behaviour of these systems are discussed, namely the friction-less motion with the consequent scattering suppression in the Landau picture and the establishment of persistent currents in the case of rotating condensates. Moreover, the authors discuss the interesting regime of the superfluidity breakdown when the polariton fluid hits a spatially extended obstacle that can be natural or created in a controlled way by mean of well suited optical beams. Vortex nucleation, vortex trapping as well as the formation of oblique dark solitons are analysed in detail. In the last part of the chapter the authors show that the strong non-linearities of the polariton systems, together with their specific propagation properties can be exploited to develop a new class of optoelectronic devices for the classical and quantum information processing.

Chapters 8 and 9 are focussed on the properties of polariton condensates confined in low dimensional structures. In Chap. 8, N.Y. Kim, Y. Yamamoto, S. Utsunomiya, K. Kusudo, S. Höfling and A. Forchel discuss the properties of exciton-polaritons condensates in artificial traps and lattices geometries in various dimensions (0D, 1D and 2D). They show how coherent π-state with p-wave order in one dimensional condensate array and d-orbital state in two dimensional square lattices can be obtained. The authors point out the interest of preparing high-orbital condensates to probe quantum phase transitions and to implement quantum emulation applications. In Chap. 9, J. Bloch reviews the recent experiments performed with polariton condensates in low-dimensional microstructures. The propagation properties of polariton condensates confined in 1D microwires, together with the possibility to manipulate and control these condensates by optical means, are discussed in detail. In the second part of the chapter, the author shows how the study of polariton condensates in fully confined geometries, obtained in single or coupled micropillars, allows gaining a deep physical insight in the nature of interactions inside the condensate as well as with the environment. In the final part of the chapter, the interesting perspectives opened by the confined polariton condensates for the implementation of devices with new functionalities are briefly reviewed.

While the previous chapters are mainly focussed on the polariton quantum fluids in GaAs-based microstructures where a cryogenic temperature (4K) is needed, Chaps. 10 and 11 explore the possibilities opened by other materials to achieve polariton condensates at room temperature. Chapter 10 by J. Levrat, G. Rossbach, R. Butté and N. Grandjean presents the recent observation of the polariton condensation at room temperature (340 K) in GaN-based planar microcavities and analyses in detail the threshold of the polariton condensation phase transition as a function of the temperature and detuning. The role of the spin-anisotropy in the polariton-polariton interactions and its impact on the polarization properties of the condensate are comprehensively discussed. In Chap. 11, F. Médard, A. Trichet, Z. Chen, L.S. Dang and M. Richard present the recent progresses towards polariton condensation at room temperature in large band-gap nanostructures, namely ZnO nanowires. The unusually large Rabi splitting observed in these systems allows achieving stable polariton at room temperature, strongly decoupled from thermal fluctuations coming from lattice vibrations. Despite this behaviour, the authors show several experimental indications of polariton quantum degeneracy at room temperature.

Chapter 12, by F. Piazza, L.A. Collins, and A. Smerzi, opens the second part of the book, dedicated to the properties of quantum fluids made by ultracold atoms. In this chapter the authors discuss the dynamics of superfluid dilute Bose-Einstein condensates in the regime where the flow velocity reaches a critical value above which stationary currents are impossible. They present results for two- and three-dimensional BECs in two different geometries: a torus and a waveguide configuration, and also discuss the behavior of the critical current, establishing a general criterion for the breakdown of stationary superfluid flows.

Chapters 13 and 14 are devoted to turbolence effects in atomic BECs, that are particularly appealing as quantized vortices can be directly visualized and the interaction parameters can be controlled by Feshbach resonances. In Chap. 13, M. Tsubota and K. Kasamatsu review recent important topics in quantized vortices and quantum turbulence in atomic BECs, providing an overview of the dynamics of quantized vortices, hydrodynamic instability, and quantum turbulence. In Chap. 14, V.S. Bagnato et al. discuss their recent observations of quantum turbolence with a condensate of ^{87}Rb.

In Chap. 15, Y. Castin and A. Sinatra discuss the coherence of a three-dimensional spatially homogeneous Bose-condensed gas, initially prepared at finite temperature and then evolving as an isolated interacting system. They review different theoretical approaches, as the number-conserving Bogoliubov approach that allows to describe the system as a weakly interacting gas of quasi-particles, and the kinetic equations describing the Beliaev-Landau processes for the quasi-particles. They show that the variance of the condensate phase-change at long times is the sum of a ballistic term and a diffusive term, with temperature and interaction dependent coefficients, and discuss their scaling behaviors in the thermodynamic limit.

Chapter 16, by R.P. Smith and Z. Hadzibabic, review the role of interactions in Bose-Einstein condensation, covering both theory and experiments. They focus on harmonically trapped ultracold atomic gases, but also discuss how these results relate to the uniform-system case, which may be relevant for other experimental systems, and for theory in general. Despite the fact that the phase transition to a Bose-Einstein condensate can occur in an ideal gas, interactions are necessary for any system to reach thermal equilibrium and so are required for condensation to occur in finite time. The authors discuss this point clarifying the effects of interactions both on the mechanism of condensation and on the critical temperature, and then review the conditions for measuring the equilibrium thermodynamics. They also discuss the non-equilibrium phenomena that occur when these conditions are controllably violated by tuning the interparticle-interaction strength.

In Chap. 17, T. Mukaiyama and M. Ueda provide an overview of theories and experiments on the thermodynamics of Fermi gases at unitarity, where the scattering length diverges, that is characterized by a universal behavior.

Finally, in Chap. 18, G. Barontini and H. Ott introduce the scanning electron microscopy (SEM), that represents one of the most promising techniques for probing and manipulating ultracold atomic systems with extremely high resolution and precision. Thanks to its extremely high resolution, below 100 nm, and to the single-atom sensitivity, the SEM method permits the observation of in-situ profiles of trapped Bose-Einstein condensates and of ultracold clouds in one- and two-dimensional optical lattices. Moreover, the single lattice sites can be selectively addressed and manipulated in order to create arbitrary patterns of occupied sites.

We hope this book will be a useful introduction to a wide audience of researchers who wish to approach the physics of quantum fluids and be updated on the last fascinating achievements in this cutting-edge research field. Last but not least, we would like to thank all the contributors for their effort in making this project possible.

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