Preamble

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Forty years ago, twenty years after the discovery of the laser, physicists were developing laser cooling methods for ions trapped in electromagnetic fields. From the 1980s onwards, these techniques were refined and extended to atoms, thanks to the audacity and inventiveness of a generation of pioneering researchers. Actually, it was necessary to succeed simultaneously in trapping and cooling samples of atomic gases in a vacuum at a distance from any wall. Spectacular results followed and extraordinarily low temperatures were quickly reached, very close to absolute zero. The field of "cold atoms" was born, rewarded by successive Nobel prizes, first of which was awarded in 1997 to William D. Phillips, Steven Chu and Claude Cohen–Tannoudji, last in 2022 to Alain Aspect. Gaseous samples of a few thousand to a few billion atoms can be prepared at a few millionths of a degree above absolute zero, which means that the particles move at extremely low speed, of the order of centimetres per second. At these extreme temperatures, the behaviour of matter changes and its properties can only be described using quantum mechanics and the wave properties of particles. New physical phenomena have been discovered and innovations have followed the theoretical and experimental progress of the research. Initially imagined as a wonderful method for perfecting atomic physics, cold atoms have gradually proved to be powerful tools for research in cross-cutting fields of physics, such as condensed matter and even high-energy physics. These atoms are now referred to as 'quantum gases' at such low temperatures that their collective behaviour is modified by the laws of quantum mechanics.

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The field of quantum gases began in the United States and Europe and has since grown dramatically around the world. Today, it continues to attract successive generations of the brightest students from all countries. This continuing success is partly due to the flexibility of the studies that each experiment allows: the density of the gas, its temperature, the geometry of the samples, the strength of the interactions between the particles, etc. can be varied. The set-ups are certainly quite complex, but remain on a human scale, allowing everyone to learn mastering many techniques. In addition, the field of quantum gases generally combines theory and experiment, which is an additional attraction for the researcher who likes to understand the whole subject. Nowadays, cold atoms are like lasers. On the one hand, they are still objects of study that research is trying to perfect: the limit of extreme temperatures is being pushed back further and further to the vicinity of absolute zero, densities are being varied from a few billion atoms per cm^3 to a few isolated atoms, the range of cooled particles (atoms, ions, molecules, clusters, etc.) is being extended, and devices are being miniaturized and simplified. On the other hand, quantum gases provide usable tools to try to understand more and more complex phenomena such as N-body physics or quantum transport, as well as to explore the conceptual foundations of quantum mechanics. They are part of what is known as the second quantum revolution, which results from the possibility of isolating and visualizing single particles (atoms, ions, photons, etc.), and also of implementing the phenomena of quantum entanglement, the basic concept of quantum mechanics. Quantum gases are thus well positioned in the emerging field of quantum technologies, which is currently the subject of a spectacular global effort, particularly in Europe where the European Union has been deploying a flagship programme with significant resources since 2017.

The book presents the most recent developments in quantum gas physics. As a follow-up to Erwan Jahier's "Cold atoms" published in 2010 in the same collection, it traces the exceptional growth of the field over the last ten years. The book explores the multiple axes along which this field of research unfolds, without aiming at an impossible exhaustiveness. Each chapter is written by one or more authors, all of whom are active researchers. They describe in pedagogical but precise terms the state of progress of research in their field. The whole book is coordinated by three researchers who ensure its coherence.

After a brief review of the physics of the interaction of atoms with light, the first chapter describes the succession of methods that made it possible to produce and understand the cooling of dilute gases to extremely low temperatures and to trap these gaseous samples levitating in vacuum. This chapter also reminds the first major breakthrough, the experimental demonstration of Bose–Einstein condensation. Chapter 2 is devoted to the very significant advances in physics metrology that cooled quantum systems have enabled. There has been steady progress in the accuracy of atomic clocks in the microwave and then optical range, which is of particular importance for the future definition of the second. Other types of cold atom instruments such as interferometers are also maturing. This opens up new possibilities to probe the fundamental laws of physics. Chapter 3 shows how the increasing control of atomic cooling, quantum states of light and the interaction between light and matter have found a new field of application in recent years with quantum information networks. The linear and non-linear operations required for the storage and processing of quantum information are described in this chapter and how cold atoms have made it possible to develop various efficient devices. Chapter 4 details the possibilities opened up by quantum gases in the field of quantum simulation. The aim is to answer questions raised by the physics of systems consisting of many interacting quantum objects with the help of another, more easily manipulated quantum system, such as cold atoms assembled in optical lattices, or trapped one by one by optical tweezers and arranged to form artificial crystals. Applications include quantum magnetism and superconductivity. Chapter 5 deals with wave scattering and disorder from a theoretical point of view. Cold atoms can play the role of these scattered waves when immersed in a disordered optical medium. In the field of transport, the effect of disorder is specifically taken into account even in the presence of interactions between particles. Situations where disorder makes it impossible to return to equilibrium are also described.

Chapter 6 extends the physics of cooled quantum gases to ions. The trapping methods are different from those for cold atoms, but many applications are common: precision measurements, spectroscopy, collision studies, quantum simulation and information. Cooled ions are also the tools of choice for fundamental experiments such as antimatter research. Finally, chapter 7 extends cooling methods to molecules. Cold molecules can be obtained by combining cold atoms by various optical or magnetic methods. Recently, alternative methods for direct cooling of molecules to temperatures as low as those achievable with atoms have also been developed. The applications are diverse, ranging from quantum simulation and information to the control of chemical reactions. Cold molecules also open the way to new tests of fundamental physics. This book as a whole is designed for anyone interested in science and technology. It is aimed in particular at students in preparatory classes and at undergraduate and graduate students. It may also be useful to young – and not so young – researchers who are approaching the field of quantum physics, and to all those who are interested in quantum technologies, a subject that is in full development. The book contains very few equations, but many figures, sketches and colour illustrations that make it attractive and relatively easy to read. It aims to share with a wide audience the passion that drives all the authors, all of whom actively engaged in their research.