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Ultra-Cold Atoms, Ions, Molecules and Quantum Technologies

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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.

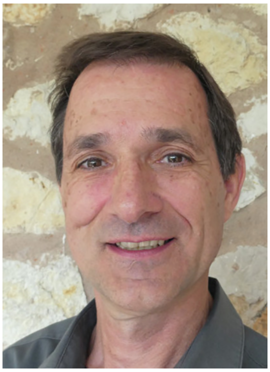
Chapter 6 extends the physics of cooled quantum gases to ions. The trapping methods are different from those for cold atoms, but many applications are common: precision measurements, spectroscopy, collision studies, quantum simulation and information. Cooled ions are also the tools of choice for fundamental 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.

Coordinators, Contributors, Sponsors and Acknowledgments

The Coordinators

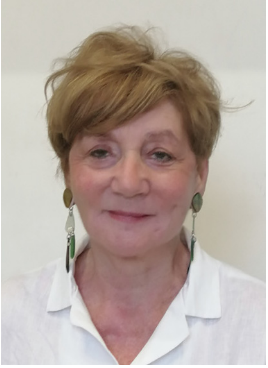
The present book is collectively written by nineteen researchers whose names are recorded at the head of each chapter and given below. Coordination of this book has been done by Robin Kaiser, Michèle Leduc, and Hélène Perrin.

Robin Kaiser



Robin Kaiser is a research director at CNRS. He started his career in atomic physics at École normale supérieure with a PhD thesis under the supervision of Alain Aspect, in the group led by Claude Cohen–Tannoudji. He then did a postdoctoral stay at Harvard University in Gerald Gabrielse's group, before joining Alain Aspect as a research fellow at CNRS to start a new activity in cold atoms at the Institut d'Optique. Since 1996, Robin Kaiser is heading the cold atoms team at the Institut de Physique de Nice. His research work focuses on light scattering by cold atoms, combining cold atom physics with mesoscopic physics, and localization of light and quantum optics. He has initiated studies of intensity correlations in astrophysics, taking up the historical studies of Hanbury–Brown and Twiss with the modern tools of quantum optics. He is also the director of the "Cold atoms" GDR (French research network) since its creation.

Michèle Leduc



Michèle Leduc is a research director emeritus at CNRS. Her career in atomic physics was mainly spent at the École normale supérieure in Paris, in the Laboratoire Kastler Brossel named after its founders Alfred Kastler (Nobel laureate in 1966) and Jean Brossel. In 1993 she joined the laser cooling team led by Claude Cohen Tannoudji, Nobel laureate in 1997. Her most recent research work focuses on Bose–Einstein condensates of metastable helium. She coordinated the outreach activities of SIRTEQ, the research network on quantum technologies in the Ile-de-France region up to late 2021. She is editor of science books for the CNRS and for EDP-Sciences. She was a member of the CNRS Ethics Committee (COMETS) from 2012 to 2021.

Hélène Perrin

Hélène Perrin is a research director at CNRS. She prepared a PhD thesis at the Laboratoire Kastler Brossel under the supervision of Christophe Salomon on laser cooling of atoms in an optical trap. She did a postdoctoral stay at the CEA on two-dimensional electron gases with Christian Glattli. She then was recruited as a research fellow by CNRS at the Laboratoire de physique des lasers at Paris Nord University, where she currently leads the BEC team. Her research focuses on Bose–Einstein condensates confined in radio frequency traps and more specifically on their superfluid properties. She teaches at the École normale supérieure and at the University of Paris. She is regularly invited to give lectures in international summer schools such as the Physics School at Les Houches. She coordinated the Quantum Simulation axis of the SIRTEQ network together with Pascal Simon and is a board member of the "Cold atoms" French research network. She is now head of QuanTip, the new research network on quantum technologies in Ile-de-France.

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The researchers who wrote the different chapters of this book are: Baptiste Allard, Juliette Billy, Nadia Bouloufa-Maafa, Nicolas Cherroret, Daniel Comparat, Olivier Dulieu, Laurent Hilico, Vincent Josse, Robin Kaiser, Martina Knoop, Bruno Laburthe, Thierry Lahaye, Michèle Leduc, Hans Lignier, Jérôme Lodewyck, Franck Pereira dos Santos, Hélène Perrin, Goulven Quemener, Jakob Reichel. These researchers work in CNRS laboratories most of them associated to various universities. The coordinators thank all the authors for their kind cooperation to the present collective enterprise.

The sponsors

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Cold Atom GDR

The "Cold atoms" GDR network was created in 2012. This network of more than 20 laboratories across France coordinates activities in the field of cold atoms in France, structures the training of young PhD students, organizes meetings and conferences, distributes resources and contributes to the influence of the field.

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Special thanks go to Alain Aspect, Nobel laureate 2022, a major contributor to cold atom research, for agreeing to write a fascinating and well-documented preface tracing the evolution of the field over the past decades. The thanks of the coordinators and contributors also go to the following people: France Citrini, Pierre Cladé, Agnès Henri, Antoine Heidmann, Lucile Julien, Michel Le Bellac, Lucie Marignac, ChristopheWestbrook.

Preface

Fifteen miraculous years: bypassing impossibility theorems

Alain Aspect

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Physics Nobel laureate 2022

When Michèle, Hélène and Robin asked me to write a preface for this book, it was impossible for me to refuse, but I found it difficult to embark on the somewhat conventional exercise of saying something positive about each chapter, even though reading them convinced me of their exceptional quality. In fact, this reading made me realize that cold atoms, once an object of advanced research, have become today a tool for multiple applications in the field of fundamental research and quantum technologies, of which this book gives a good sample. Thinking of the potential readers — the general public curious about the current developments of science, but also students engaged in a master or even a thesis using cold atoms — I thought it would be a pity if they were totally unaware of the exciting adventure we all experienced in developing this tool. I therefore decided to share with them some memories of the emergence of this field as it matured. I had the privilege of participating at the Cold Atoms group of Collège de France and Laboratoire Kastler Brossel (LKB) of the École normale supérieure in paris, and then at the Laboratoire Charles Fabry de l'Institut d'Optique in Orsay and Palaiseau.

So here are some personal memories of the early years of laser cooling of atoms leading to the gaseous Bose–Einstein condensates, the basic tools for the wonderful applications described in this book. This is not a tutorial of science history, but it recalls how I experienced this history, or more exactly what I remember. It is biased by the places from which I observed it, and above all by my own obsessions: forgetting nothing of the mistakes and disappointments, the good ideas and the lucky

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breaks, by putting them in the context of the evolution of the great concepts of physics. I hope that it may be a useful lesson for young physicists who are starting out in the field, and that it can interest the "curious amateurs" who should not believe that scientific discovery is a long quiet river. During these fifteen years, from 1985 to 2000, several barriers considered as ultimate limits were overcome, or rather bypassed. The lesson is obvious: one should not be stopped by impossibility theorems without double thinking about them. There might exist situations where these no-go theorems do not apply, that can be discovered by theoretical reflection or, more often, by doing experiments, letting Nature show the way to those who can see it. One should not underestimate the role of luck, the so-called "serendipity", from which we happen to find better than what we looked for.

The years 1985–1988 were extraordinary.[1] In the autumn of 1985, the "cold atoms" team of the Kastler Brossel Laboratory and Collège de France around Claude Cohen–Tannoudji — the three 'musketeers' Jean Dalibard, Christophe Salomon and myself—was hard at work. Our first apparatus was quite modest compared to the sophisticated set-ups of today: an atomic beam of cesium, a laser diode to act on the transverse distribution of the atomic velocities, and a hot wire detector to analyze the profile of the beam after two meters of propagation. We were plotting the results point by point, by hand, on graph paper; Claude was in charge of such plots when he spent time with us in the laboratory. We were trying to demonstrate "blue molasses cooling", a new mechanism for cooling atoms with lasers detuned from the atomic resonance to the short wavelength side.[2] The idea came from the dressed atom model used by Jean and Claude to give a simple image of the dipole force, one of the two radiative forces. It was the first occurrence of what we would call later the "Sisyphus effect". Then we received the tremendous news that the Bell Labs team—Steven Chu, Arthur Ashkin and their colleagues—had succeeded at keeping atoms "stuck" for a fraction of a second in an optical molasses, at the intersection of three pairs of lasers "red" detuned below the atomic resonance frequency.

The idea had been proposed ten years earlier by Theodor Hänsch and Arthur Schawlow, considering that the resonant pressure force, the other radiative force,[3] varied with the atom velocity: this was therefore called "Doppler cooling". With six waves detuned below the atomic resonance frequency converging on the gas, any movement of the atom was expected to cause a force opposing the movement, since the wave facing the atom has an apparent frequency approaching resonance due to the Doppler effect. The result announced by the Bell Labs physicists[4] was sensational:

[1]Steven Chu, Claude Cohen-Tannoudji and William Phillips received the 1997 Physics Nobel Prize for their works on cooling and trapping of atoms with lasers during these years. See their Nobel conferences:

Chu S. (1998) The manipulation of neutral particles, *Rev. Mod. Phys.* **70** (3), 685–706.

Cohen-Tannoudji C.N. (1998) Manipulating atoms with photons, *Rev. Mod. Phys.* **70** (3), 707–719.

Phillips W.D. (1998) Laser cooling and trapping of neutral atoms, *Rev. Mod. Phys.* **70** (3), 721–741.

[2]Aspect A., Dalibard J., Heidmann A., Salomon C., Cohen-Tannoudji C. (1986) Cooling atoms with stimulated emission, *Phys. Rev. Lett.* **57** (14), 1688–1691.

[3]Notions necessary to understand this introduction can be found in the first chapter of this book.

[4]Chu S., Hollberg L., Bjorkholm J.E., Cable A., Ashkin A. (1985) 3-Dimensional viscous confinement and cooling of atoms by resonance radiation pressure, *Phys. Rev. Lett.* **55** (1), 48–51.

the atoms remained observable at the intersection of the laser beams for almost a second, a time six orders of magnitude longer than usually allowed when observing atoms moving at hundreds of meters per second at room temperature. The measured temperature was claimed compatible with the theoretical prediction of 240 μK, well below that of most existing cryostats. Thus was achieved the first major objective of the teams engaged in this emerging field, Bill Phillips and Hal Metcalf, Jan Hall, Steven Chu and Arthur Ashkin,[5] Dave Pritchard, and Vladilen Letokhov, author of pioneering proposals, but lacking experimental facilities at the end of the Soviet era.

The second major objective was the trapping of neutral atoms. As early as 1985, Bill Phillips' team had succeeded at the magnetic trapping of sodium atoms "stopped" at the end of his Zeeman slower in a minimum of magnetic field.[6] The magnetic trapping method was only valid for paramagnetic atoms, and laser trapping remained a major goal.

An optical molasses is not a trap: the atoms are "stuck" in it by an incredibly intense viscous force (proportional to the velocity with a negative coefficient), but they nevertheless end up diffusing out of the volume where the laser beams focus, as an attractive force towards the center of the trap is lacking. There was a theoretical controversy among theorists about the possibility of a genuine trapping of neutral atoms with light. A famous article by J.P. Gordon and A. Ashkin had asserted the impossibility of achieving this with the resonant radiation pressure force.[7] They had established a theorem for the radiation pressure force called "optical Earnshaw's theorem", equivalent to the impossibility of trapping an electric charge with electrostatic fields, known as Earnshaw's theorem in English speaking countries, and as Gauss theorem in France. Scientists had therefore turned to the other radiative force, the dipole force. It was predicted that dipole force trapping would provide a potential well, *i.e.* an authentic trapping potential around a maximum of the intensity of a red-tuned laser. Unfortunately, calculations also predicted that the inevitable quantum fluctuations of this trapping force, linked to the spontaneous emission of photons, would heat the atoms, which would be rapidly ejected from the potential well. It seemed that there was a no-go theorem for trapping with either force. The most sophisticated solutions were imagined to overcome that apparent impossibility to trap atoms with light, but it is the simplest one which worked, as mentioned in 1983 in a theoretical article by Claude, Jean and Serge Reynaud,[8] and demonstrated experimentally in 1986 by the group of Chu and Ashkin.[9] It was based on a dipole trap alternated with optical molasses. Atoms, which are massive, react

[5]Nobel laureate 2018 for optical trapping with optical tweezers and their application to biological systems.

[6]Migdall A.L., Prodan J.V., Phillips W.D., Bergeman T.H., Metcalf H.J. (1985) 1st observation of magnetically trapped neutral atoms, *Phys. Rev. Lett.* **54** (24), 2596–2599.

[7]Ashkin A., Gordon J.P. (1983) Stability of radiation-pressure particle traps – an optical Earnshaw's theorem, *Opt. Lett.* **8** (10), 511–513.

[8]Dalibard J., Reynaud S., Cohen-Tannoudji C. (1983) Proposals of stable optical traps for neutral atoms, *Opt. Commun.* **47** (6), 395–399.

[9]Chu S., Bjorkholm J.E., Ashkin A., Cable A. (1986) Experimental observation of optically trapped atoms, *Phys. Rev. Lett.* **57** (3), 314–317.

only to the time average of both the trapping effect of the dipole trap and the cooling effect of optical molasses. Another possibility was found to bypass the optical Earnshaw's theorem, thanks to the internal multilevel structure of the atoms: the celebrated Magneto-Optical Trap, suggested by Jean and demonstrated by Chu and Pritchard.[10]

After the achievement of the two main initial objectives – cooling of atoms to the lowest temperatures ever obtained, trapping of these atoms –, was the game over? Was the subject of cooling and trapping neutral atoms exhausted? In fact, Nature would be generous with those who chose to pursue the subject.

In early 1988, we were alerted by a phone call from Bill Phillips: he had observed some totally unexpected results on the optical molasses he had created at almost the same time as Steve Chu. He was developing, with his team at NIST, new methods to measure the obtained temperature. All these methods converged towards the conclusion that the observed temperature was much lower than the one announced by Chu's team, clearly lower than the one predicted by the simple theoretical model used so far: Phillips' group announced a temperature not exceeding 40 μK[11] instead of Chu's 240 μK, as predicted by the simple theory. Moreover, he had made incomprehensible observations in the framework of the Doppler molasses model: a difference in intensity between two counter-propagating laser beams, which should have led to the rapid loss of atoms under the effect of the non-zero difference in radiation pressures, did not seem to particularly affect the molasses. Christophe and Jean immediately started to investigate the question experimentally, while Claude and Jean took up the theoretical question from every possible point of view in an attempt to understand these surprising and exciting results, contradicting the Murphy's "law" that "if things do not happen as expected, then it's bound to be worse than expected".[12]

The suspicion soon arose that, unlike the two-level atom model used up to that point, "two-level atoms do not exist in the real world, and moreover atoms used in experiments are not one of them" – according to an interesting statement by Bill Phillips, which has remained famous. Indeed, both Bill's sodium atoms and Christophe's and Jean's cesium atoms have a hyperfine structure in the ground state, and this state breaks down into different sublevels whose energies vary according to the intensity and polarization of the light that illuminates them: this results in the famous light shifts studied by Claude in his PhD thesis 30 years earlier. The remarkable Sisyphus model would soon emerge, in which the optical pumping of Kastler and Brossel together with Claude's light shifts combine to force the atom to lose its kinetic energy by constantly climbing up the potential hills of the light displacements; during the climb, rather upwards, the optical pumping would abruptly put them back at the foot of a new hill, associated with another sublevel,

[10] Raab E.L., Prentiss M., Cable A., Chu S., Pritchard D.E. (1987) Trapping of neutral sodium atoms with radiation pressure, *Phys. Rev. Lett.* **59** (23), 2631–2634.

[11] Lett P.D., Watts R.N., Westbrook C.I., Phillips W.D., Gould P.L., Metcalf H.J. (1988) Observation of atoms laser cooled below the doppler limit, *Phys. Rev. Lett.* **61** (2), 169–172.

[12] Note that this "law" is quite useful when it is considered for security of potentially dangerous installations such as dams or nuclear plants.

without any change in the kinetic energy. The famous ICAP conference (International Conference on Atomic Physics), hosted in Paris in the summer of 1988, endorsed Bill Phillips' experimental results, and Jean and Claude's Sisyphean interpretation,[13] while Steven Chu gave his own interpretation, also based of course on the existence of several sublevels.

Steven Chu had corrected downward his first experimental value, which was wrong for a subtle reason. His first assessment was based on the so-called "release and recapture" method: at the temperature of several hundred microKelvin the atomic velocities were such that if the molasses lasers were turned off for a few milliseconds before being turned back on, the atomic cloud had spread out ballistically, enough for a significant fraction of the atoms to be recaptured. A model based on the Maxwell–Boltzmann distribution allowed calculating the lost fraction which increased with temperature, and it was sufficient to evaluate the temperature corresponding to the observation. But in fact, as understood after Bill Phillips' discovery, at the much lower temperatures of the molasses, the atomic velocities of the released atoms were too low, when the molasses lasers were turned off, to cause a rapid expansion of the cloud: the dominant effect was that of gravity. In a way, the molasses "fell like a stone", which of course led to a loss of atoms during the recapture, but the estimation of the value of this loss by the Maxwell–Boltzmann distribution was totally wrong. And as it happened, by chance, that the obtained value was not very different from the theoretical prediction, one can understand the publication of a wrong result. Let Steven Chu himself draw the lesson of his misadventure in his Nobel lecture: 'Our first measurements showed a temperature of 185 μK, slightly lower than the minimum temperature allowed by the theory of Doppler cooling. We then made the cardinal mistake of experimental physics: instead of listening to Nature, we were overly influenced by theoretical expectations. By including a fudge factor to account for the way atoms filled the molasses region, we were able to bring our measurement into accord with our expectations.' We must be grateful to Steve for the lesson.

The ICAP conference in Paris was the scene for another "coup de theatre" in the field of cooling. After having crossed the Doppler limit, thanks to the Sisyphus effect, one could ask what was the ultimate limit of laser cooling of atoms. One answer seemed obvious: the recoil velocity for a single photon, more precisely the temperature associated with the recoil velocity of an initially stationary atom that absorbs or emits a single photon. A simple reasoning led to this conclusion. It was based on the idea that in order to obtain cooling, a dissipative process is needed, *i.e.*, spontaneous emission, which is the only dissipative process of the atom-radiation interaction. But, the spontaneous emission in free space has a random direction. The final velocity had therefore an average uncertainty related to the "last spontaneous photon emitted" at least equal to the recoil velocity. The associated temperature – called "recoil temperature"– is four orders of magnitude lower than the Doppler "limit" in the case of sodium, *i.e.*, a few tens of nanokelvin, clearly below the Sisyphus limit. Could we reach that ultimate limit?

[13]Dalibard J., Cohen-Tannoudji C. (1989) Laser cooling below the doppler limit by polarization gradients - simple theoretical models, *J. Opt. Soc. Am. B-Opt. Phy.* **6** (11), 2023–2045.

In fact, in the winter of 1987–1988, at the exact moment when the first information on sub-Doppler temperatures was coming out, Claude and I had envisaged a radically different cooling process, based not on a frictional force that slows down the atoms, but on the "selection" of atoms subject to a Brownian motion and arriving by chance at a zero value of the velocity where they accumulate. In the process we were considering, called "Velocity Selective Coherent Population Trapping" (VSCPT), the velocity of the atoms – again with several fundamental Zeeman sublevels – evolved randomly under the effect of fluorescence cycles resulting from the action of counter-propagating lasers of the same frequency. If the polarizations of the lasers were well chosen, the atoms could fall, by chance, in a superposition state of the Zeeman sublevels which was "dark", not able to absorb any light. The atom would then remain in this state indefinitely, provided that the laser frequencies were strictly equal in the atom's frame of reference, which was only true if the atom was strictly at rest. Otherwise, it would resume its Brownian motion until falling into a dark state with zero speed. Thus, one could hope to accumulate atoms around zero velocity, by a process equivalent to Maxwell's demon. The first time this idea came up, I immediately thought of Raymond Castaing, whose statistical thermodynamics course I had taken at Orsay: he explained that no fundamental law could exclude Maxwell's demon type process, provided that the entropy removed from the cooled sample is transferred to another component of the ensemble. Here, the answer was obviously in relation with the spontaneous photons, totally disordered since they are emitted in any direction.

At that time, we were developing a setup for radiative cooling of metastable helium (He*), with two PhD students, Robin Kaiser and Nathalie Vansteenkiste (now Westbrook), with the help of the metastable helium team at LKB, who was working under the direction of Franck Laloë on quantum statistical effects. Michèle Leduc, a world specialist in lasers at the resonance wavelength of He* at 1.08 μm, as well as Pierre-Jean Nacher and Geneviève Tastevin, constantly helped teaching us how to produce He*. It turned out that the fundamental level of ^{4}He*, with angular momentum $J = 1$, had a sublevel structure perfectly adapted for VSCPT sub-recoil cooling and within a few months our team could demonstrate the one-dimensional effect, just before ICAP. We were able to reach the temperature of 2 μK, below the recoil temperature of 4 μK for metastable helium (this recoil temperature is higher than for alkalis because of the lower mass of helium). The article, submitted on July 11, 1988, was published[14] on August 15, 1988. We had asked Ennio Arimondo to join us. A decade earlier he had contributed to the understanding of coherent population trapping (non-velocity selective) observed by Adriano Gozzini in his laboratory in Pisa. This was the basis of VSCPT cooling.

The study of VSCPT cooling was to continue for several years, on the one hand experimentally with its implementation in two and then three dimensions by François Bardou, who too soon passed away, John Lawall and Michèle Leduc. It also gave rise to a totally unexpected and powerful theoretical analysis that still

[14] Aspect A., Arimondo E., Kaiser R., Vansteenkiste N., Cohen-Tannoudji C. (1988) Laser cooling below the one-photon recoil energy by velocity-selective coherent population trapping, *Phys. Rev. Lett.* **61** (7), 826–829.

astonishes me, based on a non-standard statistical phenomenon called "Lévy flight". Such an analysis was born from a meeting of Claude, François and me with Jean-Philippe Bouchaud, with whom we later wrote a book on the subject.[15] Among the most extraordinary predictions of this analysis, the unusual fact that there is no temperature limit: the temperature obtained is predicted to decrease monotonically towards absolute zero when the duration of the interaction of atoms with light increases.

It is in the field of quantum gases, the central subject of the present book, that I will take my third example of a discovery that has benefited from a "favorable nudge" of Nature: the Bose–Einstein condensation of metastable helium. Because of the unique possibility of detecting individual atoms of metastable helium, we decided, with Chris Westbrook, to develop a set up for cold metastable helium atoms in our group of atom optics at the Institut d'Optique, created in Orsay in 1993. Our long term goal was to start a program of quantum atom optics, by analogy with photon quantum optics which developed after the second world war thanks to detection methods of individual photons. This program, still in progress, had started with modest objectives when Antoine Browaeys, a new PhD student, who had taken over the He* set-up at Institut d'Optique from Guillaume Labeyrie, proposed to try to obtain Bose–Einstein condensation of the bosonic isotope ^{4}He*. The bet seemed lost in advance, since the condensation required a phase of evaporative cooling during which the atoms re-thermalize by elastic collision. Indeed, it was well known that two colliding metastable helium atoms de-excite inelastically by so called Penning ionization, releasing a huge energy (on the scale of cold atoms) of several tens of electron volts, more than enough to eject atoms from the cold sample. To this objection, Antoine replied that a Russian theorist, Gora Shlyapnikov, whom we would soon get to know better since he took a position at CNRS, had predicted a suppression of the Penning collision rate by 5 orders of magnitude (a factor of 100 000!) provided that the atoms were polarized, all in the same Zeeman sub-level $m = 1$ of the metastable $2^3\mathrm{S}_1$ state of angular momentum $J = 1$. After many discussions, Antoine convinced Chris, Denis Boiron and myself to let him embark into that project.

I will skip all the novel developments that Antoine had to invent during his thesis, but I will tell how this condensation, the only one yet seen with a metastable noble gas, was produced, with a bit of luck. Antoine had to defend his thesis (brilliant though it was) without having obtained the condensation, for administrative reasons. He then joined Bill Phillips in Gaithersburg. Two new PhD students, Alice Robert and Olivier Sirjean, had taken over the experiment and were pushing as far as they could the evaporative cooling developed by Antoine.[16] But because of the decrease in the number of atoms during the evaporation, they always arrived at a point where the signal became very weak and eventually ceased to be observable. This signal resulted from the observation of the atoms arriving on a detector located

[15] Bardou F., Bouchaud J.-P., Aspect A., Cohen-Tannoudji C. (2002) *Lévy statistics and laser cooling: how rare events bring atoms to rest*. Cambridge University Press.

[16] Browaeys A., Robert A., Sirjean O., Poupard J., Nowak S., Boiron D., Westbrook C.I., Aspect A. (2001) Thermalization of magnetically trapped metastable helium, *Phys. Rev. A* **64** (3).

five centimeters below the magnetic trap from which they had been released at the end of the cooling phase. The dispersion of the arrival times made it possible to deduce the distribution of the departure velocities, thus to evaluate the temperature, and to verify the efficiency of the cooling. Tired of seeing the signal disappearing when they pushed the evaporation a little too far, the PhD students tried a desperate maneuver: they continued the evaporation despite the disappearance of the signal. And suddenly a signal reappeared, with much cooler atoms, displaying the famous characteristic peak of Bose–Einstein condensation.[17] I do not remember if we immediately thought of the then fifteen years old story of Steven Chu's optical molasses "falling like a stone", but it did not take long for us to understand that a similar phenomenon had occurred in our laboratory: as long as the temperature had not reached a sufficiently low value, the atomic cloud spread rapidly in an isotropic way when the trap was turned off, and only a small fraction of the atoms reached the detector placed five centimeters below the trap. But below ten microkelvin, the initial velocities were so low that all the atoms fell on the detector, resulting in a dramatic increase in the effective detection efficiency. I will not expand on the other favorable element of this experiment, suffered rather than planned, but crucial: because of eddy currents, the magnetic field was submitted to a violent rotation when the magnetic trap was switched off, in a time that we could not reduce to less than a few milliseconds. But in a much shorter time, a fraction of a millisecond, about 10% of the atoms trapped in their $m = 1$ state underwent a non-adiabatic transfer to the $m = 0$ state where they were no longer sensitive to the magnetic field of the trap, even though it was still present, and they fell freely towards the detector. The distribution of arrival times allowed us to reconstruct the distribution of atomic velocities at the time of the trap cut-off, on the one hand, because the fall was not disturbed by the magnetic fields, and on the other hand, because the transfer took place in a short time compared to other characteristic times of the problem.

One week later, the He* team at ENS, around Franck Pereira dos Santos, Michèle Leduc and Claude Cohen-Tannoudji, whom we had immediately informed of our success, observed the phenomenon of condensation of metastable helium with a different method.[18] Since then, we have been able to develop as planned our program of quantum atomic optics,[19] which is still in progress, while David Clément has developed another He* experiment for a unique quantum simulator of condensed matter phenomena.[20]

I could have cited other examples of remarkable and unexpected discoveries, contradicting some "impossibility theorems", which have peppered the experimental

[17] Robert A., Sirjean O., Browaeys A., Poupard J., Nowak S., Boiron D., Westbrook C.I., Aspect A. (2001) A Bose–Einstein condensate of metastable atoms, *Sci.* **292** (5516), 461–464.

[18] Dos Santos F.P., Leonard J., Wang J.M., Barrelet C.J., Perales F., Rasel E., Unnikrishnan C.S., Leduc M., Cohen-Tannoudji C. (2001) Bose–Einstein condensation of metastable helium, *Phys. Rev. Lett.* **86** (16), 3459–3462.

[19] Aspect A. (2019) Hanbury Brown and Twiss, Hong Ou and Mandel effects and other landmarks in quantum optics: from photons to atoms, in Current Trends in Atomic Physics. Oxford University Press. Manuscript available at https://arxiv.org/abs/2005.08239.

[20] Carcy C., Cayla H., Tenart A., Aspect A., Mancini M., Clement D. (2019) Momentum-space atom correlations in a Mott insulator, *Phys. Rev.* X **9** (4).

progress in the field of ultra-cold quantum gases. But it is time to conclude this preface, by drawing some lessons from sometimes surprising trajectories of experimental physics. First, as shown from the episodes of Steven Chu's optical molasses and the observation of metastable helium condensation, one should not think that what one observes in a real experiment is systematically a degraded version of what was predicted. Nature is always more complex than our simple models, and even if it is true that this complexity is often the cause of less spectacular results than expected, it also leaves open the possibility of subtle phenomena not anticipated, like the Sisyphus effect, leading to better results than expected: an anti-Murphy's law!

I want to add a word about the proper use of impossibility theorems — I am of course talking about exact theorems, not theorems with mistakes. It is important to understand what the conditions for the application of the theorem are; then, if all these conditions are not met, it may be possible to pass the limits set by the theorem. We know the case of trapping of charged particles, considered impossible according to the Earnshaw–Gauss theorem, which in fact applies only to electrostatic fields, but neither to Penning traps nor to Paul traps, which use alternating magnetic and electric fields. I have mentioned the case of the magneto-optical trap which escapes the optical Earnshaw's theorem by not respecting the proportionality relation between the Poynting vector and the radiation pressure, again because of the multilevel structure of real atoms. I have also shown how the recoil limit, associated with cooling processes resulting from a frictional force, has been beaten by a process that is not a dissipative process in the usual sense of the term, since the atoms are cooled not by a frictional force but by a selective accumulation in velocity space.

Far from being a science of the past, as it was sometimes considered, the physics of atoms interacting with light, at the origin of the development of quantum physics at the beginning of the 20th century, experienced an extraordinary revival with the cooling of atoms by laser, followed by the study of ultra-cold quantum gasses thus created. In AMO physics, we have a priori exact theoretical descriptions, but we must develop simplified models to solve the sometimes inextricable equations and to obtain simple images giving fruitful intuitions. It is the confrontation of these simplified models with experimental observations that can give rise to the happy surprises of which I have given some examples. There is no doubt that new and equally extraordinary surprises can be expected by the researchers. It will be exciting to follow these new developments, to which the reading of this book will have prepared the reader.

Palaiseau and Oléron, June 2020