TAMING ATOMS

The Renaissance of Atomic Physics

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Preface

Over the last four decades, we have witnessed a true revival of atomic physics. This revival has nothing to do with the nuclear phenomena, nuclear plants, and nuclear weapons that immediately jump to mind when people hear the term 'atomic physics.' The modern achievements of atomic physics concern very small energy scales, thanks to the rapid and important developments in controlling the motion of atoms. The awarding of four Nobel Prizes in Physics sealed these achievements: the first prize, in 1997, to S. Chu, W. Phillips, and C. Cohen-Tannoudji for slowing down and trapping the motion of atoms; the second, in 2001, to W. Ketterle, E. Cornell, and C. Wiemann for achieving Bose–Einstein condensation in alkali gases; the third, in 2012, to S. Haroche and D. Wineland for their experiments on single atoms and ions; and the fourth, in 2018, to A. Ashkin for discovering optical tweezers.

The ancient atomistic philosophy of Leucippus and Demokritus considered atoms to be restless particles in perpetual motion. This philosophical perception gained the status of scientific theory with the development of statistical physics and chemistry in the 19th century. Since then, we have learned that gas atoms, even at ordinary temperatures, move rapidly into random directions in space. For example, at room temperature, atoms have a mean speed equivalent to that of a jet plane. For the last 40 years, scientists have managed to master this mischievous motion, having achieved a drastic reduction in atomic speed and trapping, i.e., restricting the motion of an atom to a particular area in space. Thanks to these achievements, we are now able to construct samples of atoms and molecules whose average kinetic temperatures are about one billion times smaller than the temperature of interstellar space. From this standpoint, we are in a position to argue that science nowadays has reached two boundaries of cosmogenic significance. On one hand, experiments carried out at the CERN accelerators have achieved temperatures of 10^{12} K, the highest to ever occur in physics experiments. These are the temperatures that prevailed during the birth of the Universe during the notorious *big bang*. On the other hand, as was mentioned earlier, with Bose–Einstein atomic condensates, we reached the lowest temperatures of 10^{-9} K. These are the temperatures predicted to prevail during the expansion phase of the Universe. In practice, as W. Ketterle has pointed out, we have foretold Nature. The history and future of the Universe can now be reproduced in our laboratories.

These achievements have cleared the way to a series of theoretical, experimental, and technological applications in the microworld of atoms. The control of atomic motion led to the study of phenomena in areas that until now have not been experimentally accessible. Phenomena and applications such as *Bose–Einstein condensation*, *quantum jumps*, *"Schrödinger's cat,"* *quantum cryptography*, *quantum computers*, *optical lattices*, *atomic conveyors*, and *quantum simulators* are now routinely reproduced in laboratories of atomic physics around the world. New research fields such as *atom optics* and *atomtronics* are emerging, while the accuracy of measuring devices, such as *atomic clocks*, is being projected to incredible levels. Biological applications are also very important, where, with *optical tweezers*, we acquire new tools for manipulating cellular and subcellular particles. The common basis of these achievements are the forces that *laser* light exerts as it interacts with atoms, molecules, and tiny particles. It would not be an exaggeration to say that, just as the whip is a tool that helped humans tame the horse (and indeed master it), thus leading to advances in agriculture, hunting, and martial arts, the laser is the tool with which we have tamed atoms in a gaseous state, succesfully slowing them down and trapping their motion, thus paving the way for applications that have now surpassed the boundaries of our imagination.

The content of this book is organized in two main parts. The first four chapters follow a historical/chronological sequence. Chapter 1 gives an overview of the evolution of atomic physics—from the time when ancient philosophers contemplated atoms to the current quantum revolution. Emphasis is placed on a number of issues and concepts that will be needed to understand the rest of the book. The next three chapters present and explain the basic physical mechanisms at work behind the phenomena and achievements presented in the subsequent chapters. The final chapter presents prospects that will likely come to fruition in the near future. The terms displayed in italics are explained in the glossary at the end of the book. The book also contains an extensive bibliography, which is unprecedented for a popularization work. This decision to include a list of further reading was driven by the need to both respect the work of scientists in the field and to provide reliable, accurate information to the reader.

The publication of this book concludes an ambitious effort that has spanned several years. After completing (with some brief pauses) 30 years of research on issues relating to the motion of atoms when they interact with laser light, I thought it would be worthwhile to present the achievements of this field to the public—the "friends of physics." This endeavor began with a series of articles in the journal of the Hellenic Physical Society, *Physics News*, as well as in the Greek monthly journal, *Periscope of Science*. This series of articles constitutes the "backbone" of the book.

While writing the manuscript, I encountered difficulty in two issues. The first is that research in this field is not complete. On the contrary, every week our email inboxes receive articles and posts about new, fascinating phenomena and applications. In many cases, even distinguished researchers cannot keep up with these frenetic advances in research. But how does news of these achievements reach the public? Often this is done through mass media and social networking, or under "catchy" media headlines that appear among the daily news items on politics, sports, and lifestyle, as part of the news medias' struggle to attract more readers and advertisements. Scientific knowledge, thus, reaches the public in a form that is fragmented and detached from its history and evolution. This contributes to the complicated and even paradoxical social phenomenon of our time, namely, that the unprecedented explosion of scientific achievements coexists with a rise in religious belief and irrationalism. For scientists working in any given field, a critical task lies ahead: to do everything they can to provide society an integrated, solid, and complete picture of the advances in their field. This is their social duty in the struggle against the zeitgeist of our era.

The second problem is the common but extremely challenging task faced by professionals in a particular area of research when they have to present complex themes to nonspecialized audiences. In this context, there are places in the book where I deliberately sacrificed scientific rigor to facilitate understanding by the reader. Whether my efforts have succeeded in adequately managing this tradeoff, of course, will be judged by the readers of the book. Let me note that, as far as I know, there is no such book on the topic of cold atomic physics in the international literature of the last 20 years.

I would like to thank a number of colleagues and friends for their comments on the text: first, my colleague at King Saud University, Professor Andreas Lyras; then, Professor Christos Georgiou (University of Patras), Dr. Dimitris Patelis (Technical University of Crete), and Professor M. Babiker (University of York). I would like also to thank Mrs. Kelly Spyropoulou and Mr. Kostas Rapatzikos for their valuable comments, and Mr. P. Varelas for drawing two figures for the book.

I am also grateful to Professors R. Blatt and C. Lackner (Innsbruck University), Professor M. Padgett and Dr. J. Courtial (Glasgow University), Professor W. Ketterle (MIT), and Phil Saunders for photographic material. I thank C. W. Oates, researcher at the (U.S.) National Institute of Standards and Technology (NIST) for clarification of different aspects of atomic clock operation, and Professor Onofrio Marago (CNR-IPCF, Italy) for clarifications on the physics of optical tweezers. I would like to thank the two anonymous technical reviewers for their valuable comments, corrections, and suggestions on the manuscript. Finally, I would like to thank SPIE Press for undertaking the risk of publishing the book and, especially, Ms. Dara Burrows, SPIE Senior Editor, for her high professionalism and continuous

advice and encouragement during the editing process. It has been a great experience for me to work with her for all of these months.

Vassilis E. Lembessis
May 2020

Chapter 1
The Atom: From Philosophical Reflection to the Testimony of Science

To E. Bitsakis

1.1 A Philosophical Perspective and the Pioneers of Chemistry

Democritus and his teacher Leucippus developed *atomic theory* in classical Greece in the 5th century BC. This theory predicted that atoms are compact and indivisible entities that are in a state of perpetual and random motion, and that all of the phenomena we observe in the world emerge from the collisions between atoms. With the work of Democritus, the question of the Ionian naturalist philosophers about the infinite divisibility of matter received its answer: The atom constitutes the ultimate limit of the divisibility of matter.[1] This answer is actually what the ancient Greek word ἄτομον (atomon) reveals: ά means "not," and *τομή* (tome) means "the action of cutting," i.e., "uncuttable" or indivisible. Distinguished supporters of atomic theory in Greek antiquity were Plato and Epicurus. It must be stressed that both Epicurus and his followers went one step farther by adapting atomic theory to their moral teachings. In Roman times, interest in atomic theory was revived when the poet and philosopher Lucretius incorporated it as a prominent viewpoint into his work *De rerum natura* (*On the Nature of Things*) in the 1st century BC. With this didactic poem, atomic theory became known throughout the ancient world.[2] It is also worth mentioning that atomic theory would be included in the work of Diogenes Laertius, *Lives and Opinions of Eminent Philosophers*, in which one book was dedicated to Epicurus, while references to it exist in various writings of Cicero.[3]

Atomic theory had not only enthusiastic fans but also fanatical opponents. Already in ancient times, the theory had received the criticism of the philosopher Anaxagoras, who believed that atoms should, in turn, be made up of smaller parts. However, the Christian Church, which had an open ideological front against the philosophy of Epicurus and Lucretius and, consequently, against any theory associated with their ideas, exercised great opposition. The opposition was centered mainly on the position of the invariability of atoms, which, according to several theologians, undermines the concept of denaturation—the basis of Holy Communion. Although the criticism by Christian theologists was harsh, atomic theory was not suppressed, as it explained in a satisfactory way several simple properties of matter. In the context of this controversy, attempts were made to formulate alternative theories, such as the theory of *minima naturalia* (the lesser natural things). Atomic theory remained known, but was at the same time limited in the circles of Charlemagne's court at the beginning of the 9th century AD. In the world of Arabic intellectuals, atomic theory found a fervent supporter in the philosopher (and critic of the work of Galinus and Aristotle) Abu Bakr Muhammad ibn Zahariyā al-Razi (854–925 AD), who was best known in the West as Razi.[4]

In more modern times, the pioneers of natural science, such as Galileo, Descartes, Newton, and Hooke, were supporters of atomic theory at the level of philosophical contemplation. Hooke, in fact, linked the pressure exerted by a gas on the walls of the container containing it, with the forces exerted by the gas atoms on the walls when they collide with them. Hooke's hypothesis was consistent with the data from the experiments R. Boyle had made a generation earlier, and showed that when the temperature of a gas remains constant, its volume is inversely proportional to the pressure exerted. At the same time, in the field of philosophy, the prominent devotees of atomic theory were Giordano Bruno, Francis Bacon, and Pierre Gassenti. The latter, in fact, developed a materialist ontology based on ancient atomic theory. It is worth noting that Newton was cautious in his "flirt" with atomic theory because the Bishop of Berkeley had accused him of showing a propensity for materialism. We should point out that this historical restoration of atomic theory occurred in a radically different conceptual framework compared to the initial restoration. While in ancient times, combinations of atoms were viewed as entirely random, with coincidence being the driving force of phenomena, modern atomic theory was subject to the search for rationalism and, through this search, was also subject to attempts to justify the existence of God.

It would be another two centuries before the first empirical data supporting the atomic hypothesis would arrive. These data did not come from the field of physics, but from 19th century chemistry. At that time, chemists had succeeded in clarifying the difference between *chemical elements* and *chemical compounds*. The English chemist John Dalton suggested that the atomic structure of matter could explain the mysterious precision and stability with which chemical elements are synthesized to give chemical compounds. From that moment, atomic theory, which had been a philosophical concept, became a scientific model.

Dalton's formulation gave new impetus to preceding theoretical and experimental research. In 1858, S. Canizzaro (a Sicilian collaborator of

G. Garibaldi, who took part in the Risorgimento—the political and social movement that led to the birth of modern Italy) determined the relative weights of the atoms of most, then known, chemical elements. In this way, it became possible to determine the atomic composition of chemical compounds. Since then, atomic theory has been a fundamental aspect of chemistry. Modern chemistry thus justified the ingenious intuition of the ancient Democritus.

A very important advance made during the 19th century was the development of *statistical mechanics*, which would give further impetus to atomic theory. Scientists (including Bacon), even before the time of Galileo, believed that heat could be associated with some form of microscopic motion. James Prescott Joule's research on the conversion of motion to heat added even more credence to this idea. In 1847, Rudolf Clausius linked the *absolute temperature* of a gas to the average kinetic energy of the atoms in the gas. All macroscopic properties of gases such as pressure and temperature proved to be nothing but statistical manifestations of the chaotic motion of an enormous number of atoms. The establishment of statistical mechanics was the fruit of the efforts made by major physicists such as James Clerk Maxwell, Ludwig Boltzmann, and J. Willard Gibbs.

We must point out that it was not only purely scientific achievements that drove the progress and breakthroughs of science; philosophical views and beliefs equally impacted these advancements. At the time, the presiding current in the field of philosophy was *positivism*, a dominant figure of which was the Austrian scientist and philosopher Ernst Mach. A basic argument of this theory was that anything unobservable should be removed from scientific inquiry. Adopting this view, the chemist Wilhelm Ostwald attacked atomic theory by stating that, because we have not observed atoms, they cannot exist. According to Ostwald, atomic theory was nothing but a theoretical construction that has a mere "instrumental"—or interpretative—character. All that exists is energy. The influence of Ostwald's ideas, known in philosophy as *energeticism*, was so profound that it led Boltzmann to disfavor and depression, and, ultimately, to suicide.

Beyond the philosophical controversy, physics at that time was resting on its laurels. As the protagonists of that era believed, the basic theories—the pillars of science—had been firmly established. What remained was only the constant improvement in observational instruments that would ensure ever-more-accurate measurements of physical quantities. As William Thomson (better known as Lord Kelvin) used to tell his students, the sky of physics is clear except for a couple of clouds. But these clouds would bring cosmogenic storms.

1.2 Proclamation of Stormy Winds

The heating coils in an electric heater change colors as its temperature output rises. This heat is the so-called *thermal radiation* that is emitted by all bodies,

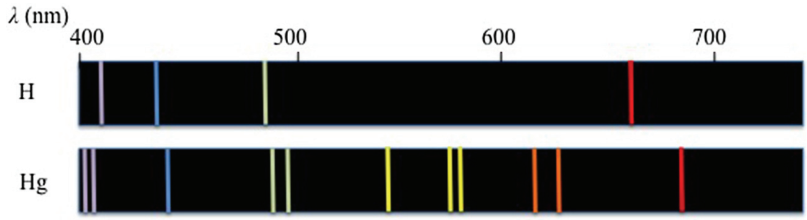

Figure 1.1 Samples of the emission spectra of hydrogen (H) and mercury (Hg), whose discrete characters (i.e., the emission of certain frequencies) are evident. (Adapted from Ref. 9.)

because Maxwell's *electromagnetic theory* predicted that, in order to produce light at a certain frequency from an electrically charged body (such as an electron), the latter would have to undergo regular periodic motion. The frequency of this motion also determines the frequency of the emitted light. However, a very reasonable objection was immediately raised. A charged body that emits radiation simultaneously loses energy. In such a case, the radius of its track would gradually shrink, resulting in a constant increase in its rotation frequency. This would lead to emission of electromagnetic radiation at continuously varying frequencies, so the spectrum could not be discrete. Even worse, the atom would be destroyed, which was in complete contrast to experimental data that showed a remarkable stability of atoms. There was no theory available to explain this large accumulation of experimental evidence and data.

A milestone in the process of defining the correct atomic model was Rutherford's experiments, where *alpha particles* (helium nuclei) were directed onto thin sheets of gold (Fig. 1.2). These experiments began in 1911 at Rutherford's lab in Manchester and produced greatly surprising results. Some of the positively charged alpha particles recoiled in the exact opposite direction when they encountered the gold leaves, literally as if they had bounced off of a wall. As Rutherford said: "It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."[10] The result of this experiment took the plum pudding model out of the running. The question of electric charge distribution inside the atom had at last been clarified: The positive charge of the atom is concentrated in a center called by Rutherford the *nucleus*.

However, the stability of the atom continued to raise the following questions: Where exactly are the electrons, and what exactly do they do? Despite the fact that Coulomb's electric force has the same mathematical structure as the law of gravitational attraction, why are atoms radically different from planetary systems? Atoms collide at tremendous speeds and emerge from them completely unchanged. Also, in addition to being stable, atoms (of the same element) are identical.

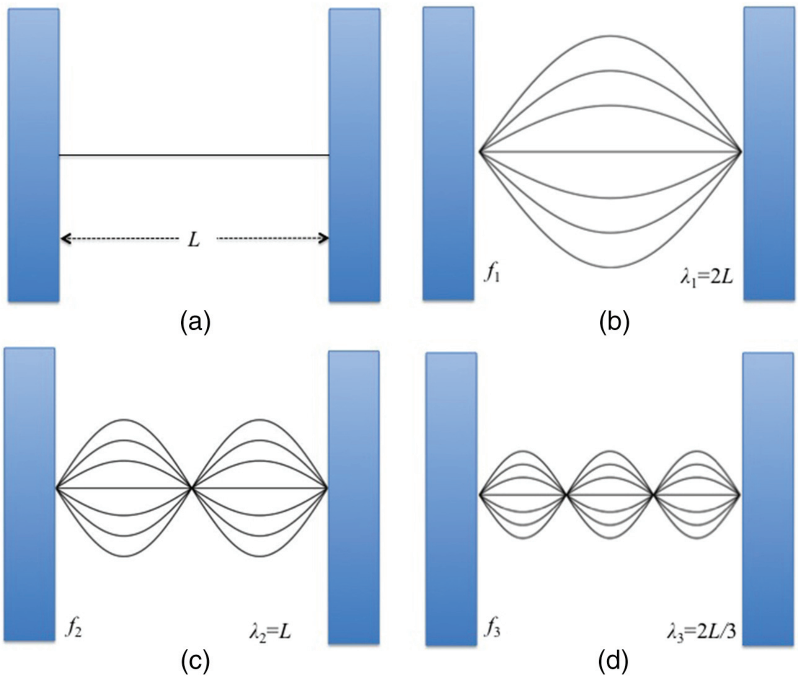

Figure 1.6 (a) A string fixed at both ends, like a guitar string; (b) a fundamental wave having a frequency of $f_1 = f_0$; (c) and (d) waves having frequencies of $f_2 = 2f_0$ and $f_3 = 3f_0$, respectively.

Standing waves also develop when a material wave is confined in a region of space, such as the electron around the nucleus. Then the wave's energy is necessarily quantized, and the electron must occupy specific states where energy is an integer multiple of the energy of the ground state.

Quantum systems, however, have other peculiarities. Suppose that a particle has the potential to be in two possible states, for example, the electron at the fundamental energy level of hydrogen, which can be found in a state with the spin UP or in a state with the spin DOWN. Quantum physics predicts that this particle may be in one or the other state, but also simultaneously in both states. This differentiates it from a classical system that is strictly in one state or another. For example, a switch in a home can be either closed or open. It is obvious that it cannot be both closed and open at the same time. Conversely, a particle such as a photon or an atom can be suspended between two states. If, for example, a photon is sent through Young's apparatus, as mentioned earlier, it can pass through both slits at once. If the particle does not interact in any way with the environment, then it continues to be in this peculiar state. If we try to disturb this "isolation," for example, by taking a measurement on the particle, this necessarily implies an interaction with the measuring device. As a result, the particle collapses into one of its two possible

Chapter 2
The Classical Period

2.1 Tribute to the Pioneers

The evolution of research into the forces that light exerts on matter is divided into two periods: the “classical” era, which spanned from 1600 to 1960, and the “modern” era, which spans from 1960 until today.[1] The criterion for this separation is the discovery of the laser light device, which for the first time provided coherent, nearly monochromatic radiation, after which research activity has spectacularly developed in recent decades.

Our story begins in 1619 when the German astronomer Johannes Kepler, in his treatise *De Cometis*, assumed that the deviation of comet tails is due to the pressure exerted on them by the sun’s rays.[1] Although the observed deviations are not interpreted solely by light pressure, this hypothesis later played an important role in understanding the role of light pressure in the Universe. At the same time, Newton claimed that light exerts pressure on material bodies. Much later, in the 19th century, the Italian physicist Adolfo Bartoli would arrive at the same conclusion, based on thermodynamic principles, while Maxwell predicted the value of light pressure on a surface by means of his electromagnetic theory. By the end of the 19th century, we would have the first experimental attempt to prove the case of light exerting pressure. In 1875, Sir William Crookes, a British chemist and physicist, presented his photoradiometer to the members of the Royal Society in London. This device included a near-vacuum tube containing a suspended metal sheet that had one purely reflective surface and one purely absorptive surface. The sheet rotated when the device was powered by light; however, despite the fact that different forces were being exerted by the light on either side of the metal, this effect could not be attributed to radiation pressure. Illumination heats the metal and causes conduction currents in it, which sets the metal sheet in rotation. The Crookes radiometer is, therefore, more of an example of hot Brownian motion than of radiation pressure, as it was not actually a vacuum inside the tube.

The classical period was highlighted by the work of P. N. Lebedev, a Russian physicist who, in 1901, managed to solve the very difficult experimental problem of measuring the pressure that light exerts on a body.[2]

emitted in a random direction. The electron cannot "calm down" when it finds itself in the quantum vacuum. This is due to the *uncertainty principle*, which is at work here, once the electromagnetic field is quantized. But what does uncertainty mean in this case? It just means that we cannot know the value of the electric and magnetic fields simultaneously with absolute accuracy. In a quantized electromagnetic field, both fields cannot simultaneously be zero. Einstein accurately introduced spontaneous emission in his attempt to interpret the spectrum of the blackbody. However, his work did not afford a detailed analysis of the real nature of spontaneous emission. This was provided later with the work of V. Weisskopf and E. Wigner.[5] The rate at which spontaneous transitions occur varies according to the characteristics of the excited level under consideration.

Stimulated photon emission is nothing more than forced electromagnetic oscillation. The electromagnetic field of light is the external stimulus at a frequency f_L, and the atom is the oscillating system characterized by an *eigenfrequency* f_0, given by the relation:

$$f_0 = (E_2 - E_1)/h, \tag{2.1}$$

where E_1 and E_2 are the energies of the two atomic states involved in the electron transition. The nature of this oscillation always depends on the relationship of these two frequencies, and its effects are maximized in the case of resonance, i.e., when $f_L = f_0$. Stimulated emission had been neglected for many years as, in ordinary equilibrium conditions, atoms prefer to be at a lower energy state than at an excited one. Consequently, stimulated light emission could not play a leading role, and this is why scientists had not given much attention to the specific characteristics of the light produced in this way. Indeed, as was mentioned, the photons generated by stimulated emission are all in phase with each other and move in the same direction as the photons that caused the transition. Simply put, each photon is a replica of another photon.* Since the 1930s, scientists have realized that this dynamic could be reversed if a state of non-thermodynamic equilibrium could be achieved, where atoms would prefer to be in an excited state. In this case, the number of excited atoms would exceed that of atoms in a lower energy state. This phenomenon is known as *population inversion* and has played a fundamental role in the generation of laser light, which will be addressed in the next chapter.

In general, intelligent people are those who can identify the details that ended up misdirecting the focal attention of others' previous studies. And as we know, the devil always "hides" in the details. In 1917, Einstein researched the momentum exchange between light and atoms in a study where he noted:

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*This statement is, however, an oversimplification since it can give the impression that with stimulated emission alone we can clone a single quantum. This is not the case, as Wootters and Zurek showed in 1982.[6]

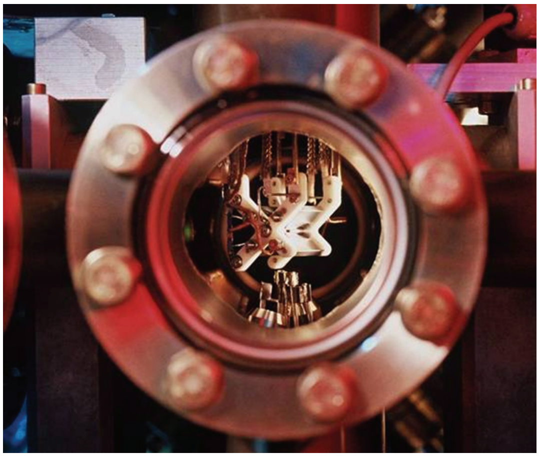

Figure 2.3 The experimental setup of a Paul trap. (Courtesy of Professor R. Blatt from Innsbruck University; photo by Christof Lackner used with permission.)

Of course, in those years, performing experiments could still be a challenge, but nothing prevented scientists from "performing" these experiments on a piece of paper. It was the era of the famous *thought experiments*, which the scientific community referred to using the German term "*gedankenexperiment*." Thought experiments were used by Einstein to develop the theory of general relativity and the *theory of special relativity*, as well as by the founders of quantum physics. This type of experiment has greatly contributed to the development of the theory of relativity and of quantum mechanics. At the same time, however, scientists believed that these *gedankenexperiments* could rarely be carried out in practice. Schrödinger himself believed that we would never be able to perform an experiment with an isolated atom or another particle.[16] As W. Phillips, one of the prominent protagonists of modern atomic physics, emphatically noted "… *it was the time when atomic physics was boring! Scientists thought they had understood the quantum mechanics and everything around the atoms. And then the laser came and we began to perform experiments that no one had imagined before. We were going to the lab and every day we were learning new things*.[17] In the following chapters, we will see how these thought experiments would become reality, proving the deep consistency of our knowledge of the world.

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Chapter 3
The Modern Period: The Advent of the Laser

To R. Loudon

3.1 And it was . . . a laser

Until the initial years following World War II, the available technology was not sufficient to perform more in-depth research on the interaction of light and atoms. The most prominent challenges were: the low intensity of the light sources, the chaotic character of light, and the inability to change the frequency of light *in vivo*, i.e, during the execution of the experiment. All of these issues were solved, once and for all, after the discovery of the laser.

The first laser was built in 1960 by T. H. Maiman. The term "laser" comes from the initial letters of the (main) words in "light amplification by stimulated emission of radiation." In other words, the laser is light coming from amplification due to stimulated photon emission. As mentioned in Chapter 1, stimulated emission creates photons having the same phase, frequency, and direction as the photons that stimulated the atom. Practically, they are perfect photon copies. No one can distinguish between the photon that caused the stimulated emission and the photon that was generated from it. This resemblance is also the basis for all of the properties of laser light and distinguishes laser light from all other light sources. Laser light properties can be summarized as follows: high intensity, monochromaticity, unidirectionality, and *phase coherence*.

Let's look at these properties in a bit more detail. The intensity of a current laser may reach the value of 10^{22} W/cm^2, as in the case of attosecond (as) lasers. These are lasers where the output beam is not continuous, but has a pulsed form with an extremely small duration on the order of 1 as (10^{-18} s). For comparison, on a sunny summer day, the intensity of light sent by the Sun is about 0.1 W/cm^2. Moreover, for *continuous-wave (CW) lasers*, the energy is concentrated in a narrow frequency range around the nominal laser frequency. That's why laser light is almost monochromatic. At the same time, this light is quite concentrated around its propagation axis—hence the

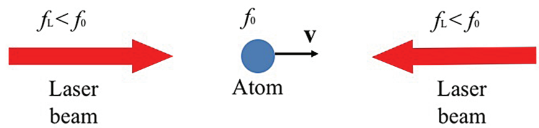

Figure 3.4 Schematic representation of the deceleration of atoms in optical molasses. Due to the Doppler effect, the atom "senses" that the frequency of the beam coming from the right is quite close to its transition frequency f_0. Consequently, the atom is in resonance with the beam coming from the right and absorbs photons "preferentially" from it. (Adapted from Ref. 8.)

"preferentially" from this beam. Something similar occurs if the atom moves in the opposite direction. Therefore, when $f_L < f_0$, the atom absorbs photons from the beam propagating in the opposite direction of its velocity. For this reason, this mechanism can slow down the atomic motion in one dimension. If we use two other corresponding pairs of laser beams along the other two directions of space, we can achieve deceleration in all directions. For obvious reasons, this mechanism is called *Doppler deceleration* (or Doppler cooling). With the help of this mechanism, the kinetic temperature of cooled atoms can reach the so-called *Doppler limit*, which for the alkali atoms is about 100 μK. To relate this concept in simpler language, again taking the sodium atom as an example, Doppler deceleration can reduce the speed of the atom to 30 cm/s. Atoms in this state move very slowly and behave like a viscous fluid. Therefore, the term *optical molasses* is used in the international literature to describe this form of an atomic gas.[9] The Doppler temperature is given by the formula

$$T_D = h\Gamma/4\pi k_B, \tag{3.2}$$

where h is Planck's constant, k_B is the Boltzmann constant, and Γ is the rate of spontaneous emission.

3.5 The First Experiments

The advent of the laser literally revolutionized our ability to interact with atoms and to change both their internal and translational states. This story began in 1962, when G. A. Askar'yan first realized that laser light can exert considerable forces on atoms.[10] In 1968, V. S. Letokhov demonstrated that the Askar'yan model could be used to trap atoms at the points of minimum intensity (nodes) or maximum intensity (antinodes) of a stationary laser wave.[11] Soon after, the first experimental results followed the theoretical work. In the early 1970s, A. Ashkin managed to trap small glass beads between two laser beams propagating in opposite directions.[12] Immediately after that, in another experiment, Ashkin managed to lift a glass bead by means of a single laser beam.[13] Quite accidentally, he discovered that the same mechanism could be used to trap living cells. Askhin understood that the

Chapter 4
Doughnuts from Light

To L. Allen and M. Babiker

4.1 A New Generation of Lasers

In the previous chapters, we have seen that the cause of the mechanical effects of light on atoms is nothing more than the momentum exchanged between photons and atoms. This exchange determines both the forces exerted on atoms and, ultimately, the atoms' translational motion. But now things become even more interesting. In this chapter we present to a new generation of laser beams that have been developed over the last few decades. These beams have quite unusual properties and even more exotic and fascinating applications. They contain optical vortices, as do many other physical systems, and, thus, are known as *optical vortex beams*. The main representatives of this large family of laser beams are the Laguerre–Gaussian and the Bessel beams,[1] whose names derive from the corresponding mathematical functions that describe them. In particular, in the scientific community, Laguerre–Gaussian beams (with which we mainly deal in this chapter) are known by the nickname "doughnuts." This name comes from the shape of the spatial profile of their intensity in a plane perpendicular to their direction of propagation. As shown in Fig. 4.1, if we direct such a beam, for instance, onto a dark wall, we will see a dark spot surrounded by one (or several) thick, bright "crown" that forms an image resembling the well-known American sweet, the doughnut.

The starting point of this new development was a seminal work carried out in 1992 by a research team in Leyden, The Netherlands.[2] In this work it was shown that the photons of Laguerre–Gaussian beams carry (with respect to the beam propagation axis) an orbital angular momentum, in addition to momentum. Simply put, as the beam propagates in space, the wavefronts simultaneously perform a rotation around the beam axis. This "twisting" of the wavefronts gives the photons of the beam an angular momentum that is actually quantized; i.e., its values can be integer multiples of a certain quantity, in particular, $l\hbar$, where l is the helical winding number (an integer number), and $\hbar$ is the *reduced Planck constant*. This orbital angular momentum may be

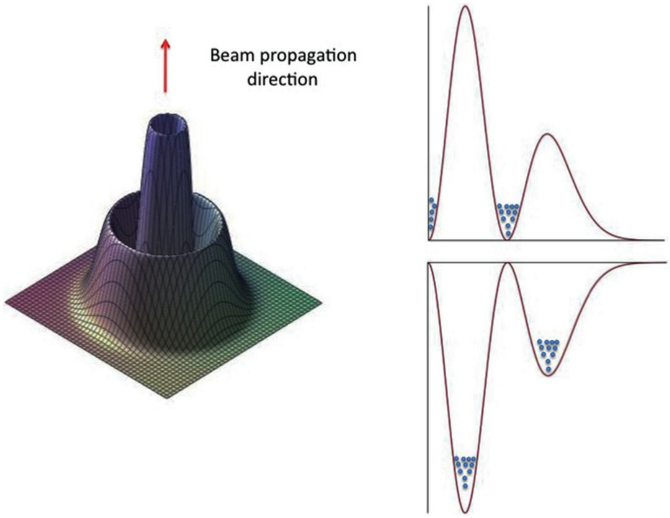

Figure 4.6 (left) The intensity profile of a Laguerre–Gaussian optical vortex. (upper right) When the beam frequency is greater than the transition frequency of the atom, the atom is trapped in the minimum-intensity areas. (lower right) Otherwise, the atom is subject to an opposite potential and is trapped in the areas where the intensity is maximum.

Another interesting application of Laguerre–Gaussian beams is the *optical Ferris wheel*,[14] in which the luminous regions are distributed with cylindrical symmetry around the beam propagation axis, as shown in Figs. 4.7 and 4.8. This intensity pattern is reminiscent of the well-known Ferris wheel in amusement parks. The optical Ferris wheel is actually a stationary wave oriented in a direction perpendicular to the propagation axis. This field is created by the interference of two vortex beams that are propagating in the same direction but have opposite winding numbers of $\pm l$. When these two

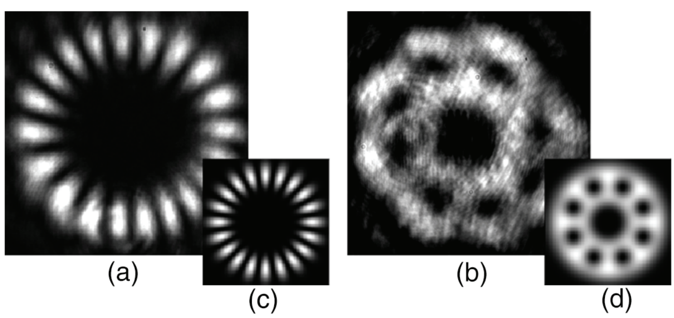

Figure 4.7 Observed intensity distribution for (a) a bright and (b) a dark lattice; insets (c) and (d) show the theoretical distributions of (a) and (b), respectively. The bright lattice is generated from Laguerre–Gaussian beams of equal intensity with $l_1 = -l_2 = 10$, and the dark lattice is generated from Laguerre–Gaussian beams with $l_1 = 3$ and $l_2 = 11$. (Adapted from Ref. 14.)

Chapter 6
The Atom Laser and Atom Optics

6.1 The Atom Laser

The transition of atoms from the disorder of the gaseous phase into the "disciplined" behavior of the condensate can be compared with the transformation of chaotic incoherent light into a laser light beam. This analogy leads directly to the definition of the *atom laser*: a device that produces a beam of boson atoms that have "escaped" from a trapped Bose–Einstein condensate.[1]

The operation of our well-known optical laser requires essentially three things: an *optical cavity*, an *active medium*, and a mechanism that allows light to escape from the cavity. Within the cavity, a huge number of atoms of the active medium interact with photons. The cavity consists essentially of two mirrors with very high reflectivity onto which the photons are reflected many times. Multiple reflections cause photons to interact continuously with atoms in the cavity, leading to a continuous generation of new photons by stimulated emission. The result is an increase in the number of photons, i.e., amplification of the beam traveling within the cavity. All of the photons have the same frequency and phase (i.e., they oscillate synchronously). Since one of the mirrors is not perfectly reflective, the photons manage to escape from the cavity, resulting in the well-known, monochromatic, and directional laser beam.

The construction of a "laser" of atoms required mechanisms similar to those needed for the construction of the optical laser (Fig. 6.1 compares an optical laser with an atom laser). The first thing was to ensure the occupation of the same state by a huge number of atoms—the analogue of having plenty of photons at the same frequency. Bose–Einstein condensation addressed this need. The next issue required the invention of a mechanism to help the atoms escape the Bose–Einstein condensate in the formation of a beam and then to propagate in space in that formation. This mechanism creates a method of trapping atoms using a magnetic field. The use of electromagnetic fields of radiofrequencies can alter the magnetic properties

Chapter 10
Quantum Simulation of Magnetic and Electric Fields

10.1 Artificial Fields with Rotating Trapped Atoms

The simulation of magnetic and electric quantum effects, which are encountered in the physics of condensed matter and concern the interaction of electrons with magnetic and electric fields, is an interesting problem, especially when working with atoms. The reason is that atoms are electrically neutral, so they cannot at first mimic the behavior of charged particles such as electrons. In this chapter, we review the ways in which we have been able to overcome this problem in systems of cold atoms interacting with laser beams. In the international literature, these simulated fields are known as *artificial gauge fields*, or simply *artificial fields*.[1]

The first method is quite simple in its conception. Since our high school years, we know that when a moving electric charge is found in a magnetic field it can be rotated thanks to the *Lorentz force* exerted on it by the field. If we managed to rotate atoms trapped in a specific area of space, we would essentially mimic the movement of charged particles in magnetic fields.[2] Indeed, it has been shown that a complete analogy can be drawn between the dynamics of an electrically charged particle and that of a neutral atom in a rotating frame of reference. The *Coriolis force* exerted on an atom in the rotating reference system is equivalent to the Lorentz force exerted by a magnetic field on a charged particle. The desired rotation of atoms within a trap is achieved when the atoms interact with laser beams such as optical vortices. As discussed in detail in Chapter 4, in this case the light exerts mechanical torque on atoms and therefore sets them in rotation within the trap. In this case, we have the appearance of a very important effect. Typically, rotating atoms are trapped in optical traps. When atoms have very low energy, they behave like quantum particles and occupy the ground state of the potential of the trap. When the rotation frequency reaches a specific value, the centrifugal force balances the force from the trapping potential and the atom is essentially converted into a two-dimensional system. The energy

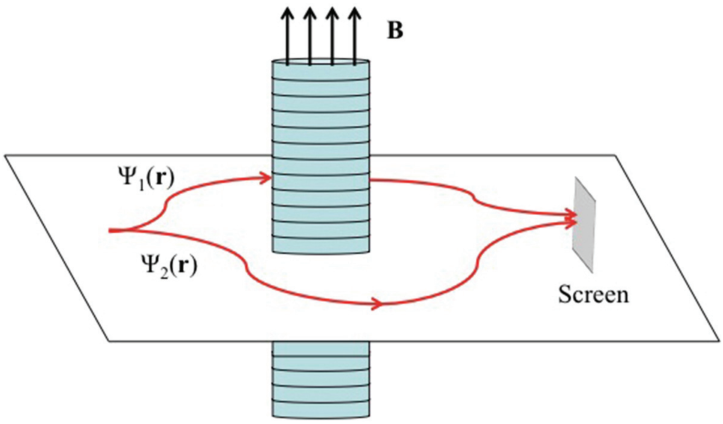

Figure 10.1 The arrangement proposed by Aharonov and Bohm consists of a solenoid of infinite length surrounded by a potential barrier such that the particles cannot enter its interior. On the screen we observe the interference of two wave materials with wave functions $\Psi_1(\mathbf{r})$ and $\Psi_2(\mathbf{r})$ passing from the left and right of the solenoid. The interference pattern we see on the screen varies depending on whether the solenoid carries a current or not, although magnetic field **B** in the particle region is zero in both cases. (Adapted from Fig. 1 in Ref. 8.)

an extra phase of a geometric character in the wave function Ψ when an atom follows a closed path. This is equivalent to the effect of a magnetic field on a moving charged particle. However, one must ask whether it is possible for a physical quantity to return to its original position after it has undergone a change. The following example is particularly enlightening.

After carefully examining Fig. 10.2, place a vector (or a pencil or an arrow—anything that can have direction) in the northern pole of a globe.

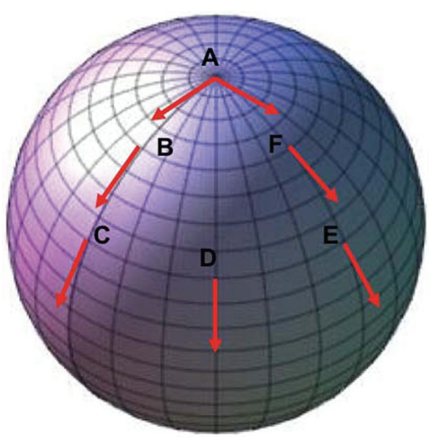

Figure 10.2 The vector is shifted parallel to meridian A-B-C and then along the latitudinal line C-D-E to meet meridian E-F-A. Moving the vector along the new meridian returns it to its original starting position A, but now it has a different direction!

Chapter 13
Optical Tweezers: The Toolbox of the Microworld

On 2 October 2018, the Swedish Academy of Sciences announced the award of the Nobel Prize in Physics for that year. Among the three honored scientists was an American physicist, A. Ashkin, who was chosen for his "pioneering research project on optical tweezers and their applications in biology," as the announcement plainly and comprehensively stated. Ashkin invented the optical tweezers, which are an extremely effective tool that helps us capture atoms, particles, viruses, and cells, and that has paved the way for unprecedented, revolutionary applications.

By "tweezers" we usually mean a tool that helps us handle things that cannot, for various reasons, be touched by the naked hands. Often handling tweezers requires particularly fine movements and increased skill because these tools are likely to pose various risks. A well-known example of this is the case of surgical medicine, where doctors come in contact with very sensitive organs via tweezers. However, in the final analysis, most examples of the use of tweezers involve handling objects from our daily lives or from, as scientists call it, the macroworld. Nowadays techniques are being developed that allow us to make tweezers for the microworld as well, using mechanisms by means of which we can manipulate and control the motion and location of micro- and nanoparticles. These particles have sizes that range from a few millimeters to several billionths of a meter, as shown in Table 13.1. Operation of the

Table 13.1 Scale of particles that can be trapped by optical tweezers and some typical examples of these particles. (Data taken from Fig. 1.3 of Ref. 1.)

Rayleigh regime	Intermediate regime	Mie regime
biomolecules, viruses, atoms, quantum dots	sperm cells, plasmonic nanoparticles, graphene, bacteria	eukaryotic cells, algae, synthetic colloids, bacteria
0.1 nm–1 nm	1 nm–1 μm	1 μm–10 μm

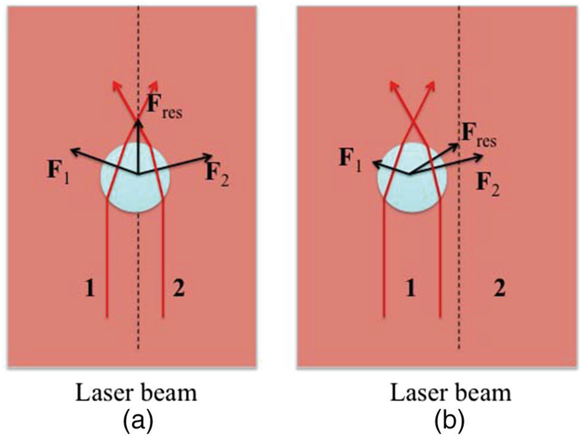

Figure 13.2 Operation of optical tweezers using a nonfocused laser beam. (a) The particle is on the axis when it is pushed upward by an axial force if there is no transverse force. (b) When the body is displaced relative to the beam axis, it receives a net transverse force directed toward the beam axis. ($\mathbf{F}_{res}$ is the resultant force of $\mathbf{F}_1$ and $\mathbf{F}_2$.)

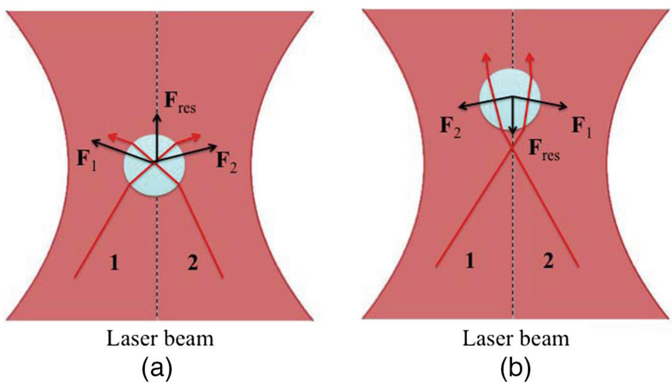

Figure 13.3 Operation of optical tweezers using a focused laser beam. (a) The particle is fixed on the beam axis and is stabilized at a particular position relative to the focus of the beam. (b) A change in the momentum of the focused rays creates a force that is always directed toward the focus, regardless of the position of the particle in relation to the focus. The final position of the particle is slightly behind the focus and can be controlled at will by simply shifting the focus of the beam.

the beam. The optical tweezers can trap particles with dimensions ranging from that of an atom up to several millionths of a meter. The forces exerted by the optical tweezers on the particles have a magnitude that can exceed 100 pN (10^{-10} N) or, in other words, about 100 times the weight of a bacterium.[2] The theoretical limit of such forces is determined by the momentum h/λ per photon in refraction/absorption, and $2h/\lambda$ in reflection. In practice, however, the value for regular optical tweezers is about 0.2–0.5h/λ, while for a

Glossary of Terms

Abrikosov lattice: A lattice of Abrikosov vortices that appears in supercurrents in superconductors. This lattice, predicted by A. Abrikosov in 1957, is built from interactions between the vortices.

Absolute temperature: A temperature that is measured with reference to absolute zero (–273.16 °C).

Absolute zero: The lowest temperature in the thermodynamic temperature scale. The international community defines absolute zero as –273.16 °C. At this temperature, the only motion of a particle is the motion induced by quantum-mechanical zero-point energy fluctuations.

Active medium: A material whose molecules, via a large number of absorption-stimulated photon emission cycles, create the light of a laser beam.

Adiabatic change: A process in which a system changes its inner state so quickly that the system does not have enough time to interact with its environment.

Aharonov–Bohm phase: A phase that appears in the wave function of a charged particle when it moves in the neighborhood of an electromagnetic field in an area where both the magnetic field and the electric field magnitudes are zero.

Alpha particle: A particle composed of two protons and two neutrons that is spontaneously emitted from an unstable nucleus during a decay. A helium nucleus is actually an alpha particle.

Angular momentum: A physical vector quantity for bodies rotating around an axis. Its magnitude L is given by the product of the momentum p ($p = mv$) and the distance r of the body's velocity direction from the axis of rotation. Its direction is given by the right-hand rule.

Antimatter: Matter composed of positrons, antiprotons, and antineutrons.

Antiparticle: For any particle in nature, there exists a corresponding antiparticle that has the same mass as the particle, but whose electric charge and other physical charges are opposite to those of the particle.