
Preface

This is a book about the *optical* trapping and manipulation of small neutral particles using the forces of radiation pressure from lasers.

This subject traces its origin back to 1969, to the time of the discovery of significant radiation pressure forces on dielectric spheres using lasers and the first experimental observation of optical trapping by Ashkin [1]* (a reference number followed by an asterisk indicates that the paper is reprinted in this volume).

At that time this author also proposed the possibility of stably trapping atoms by radiation pressure [1]*, [2]*. Radiation pressure forces are those arising from the momentum of the light itself. Over the course of the next 35 years or so the techniques of optical trapping and manipulation have made unique and revolutionary contributions to experimental studies in the fields of light scattering, atomic physics, biophysics and other areas of the biological sciences and, more recently, chemistry.

These optical manipulation techniques apply to neutral particles as diverse as: (i) small dielectric spheres in the size range of tens of micrometers down to tens of nanometers, and (ii) atoms and molecules at temperatures ranging from hundreds of degrees Kelvin down to about a nanokelvin, as well as (iii) atomic particles in Bose–Einstein and fermionic condensates in atomic vapors and newly demonstrated atom lasers. Included under (i) above are biological particles such as viruses, bacteria, living cells, organelles within cells and macromolecules.

Among the unique capabilities of optical manipulation is the simple ability to noninvasively hold a single particle fixed in space, free of any mechanical support, using a single beam of light. Sub-micrometer particles in a compact trap, such as the single-beam gradient or optical tweezers trap [3]*, [4]*, [5]*, can be localized to within a small fraction of a wavelength of light or moved over long distances of many centimeters [6]. Implied in this long distance motion is the capability of separating a single selected particle, such as a bacterium, from a mixed collection, or “*Gemisch*”, of particles. Furthermore, trapping, moving, and separation of particles can be done in controlled environments of temperature, pressure, pH, etc.

Using optical manipulation one can continuously apply controlled force to particles by moving the tweezer trapping beam or by applying an external force on a particle held within a fixed optical tweezer trap. One can measure applied forces by directly observing the displacement of particles in a trap due to applied forces or one can use optical feedback techniques, which are extremely sensitive. For physical particles one can measure gravitational, electric, magnetic, or optical forces. The feedback technique was originally conceived in order to apply a form of optical damping for stabilizing optically levitated particles in vacuum [7]*.

Using feedback techniques in biology, one can measure the minute forces of single motor molecules, such as kinesin moving on microtubules or myosin moving on actin filaments. Motor molecules also power chromosome separation in mitosis, cell locomotion through liquids by the action of flagella, and cell motion over surfaces in amoeboid motion or in tissue growth. These single molecular motor forces are in the range of a fraction of a piconewton up to about 100 pN. Large single macromolecules with molecular weights $\geq 10^6$, such as Tobacco Mosaic Virus (TMV) or microtubules, can be manipulated directly. Smaller molecules, for example the molecular motors or mechano-enzymes such as RNA or DNA polymerase, are too small to be directly manipulated by optical tweezers. However, they can be attached to small transparent dielectric spheres that are then optically manipulated. This is called the “handles technique”.

Handles and tweezer techniques are useful for studying cell–cell adhesion due to antibody–antigen binding or other lock and key type molecular recognition processes. The handles technique is also useful for applying mechanical forces on single molecules to study the elasticity and compliance of the molecule itself. Recent reviews by the author [8], [9], [10]* give overviews of the above-mentioned applications of optical trapping and manipulation techniques.

There are, of course, other techniques which exist for manipulating small particles and cells, for instance using fine microneedles [11], [12]* controlled by conventional mechanical micromanipulators or using the specialized techniques of Atomic Force Microscopy (AFM) [13], [14]. In Ref. [11] the breakage of the strong monomer–monomer bonds of actin was accomplished with microneedles. In Ref. [15] the motion of myosin on the nanometer scale was observed with needles. In Ref. [13] the breakage of receptor–ligand links was done with AFM. Rief *et al.* [14] used a stiff AFM cantilever to pull on a single titin molecule and observe the successive unfolding of coiled domains. Microneedles and AFM manipulation techniques have their own particular uses, advantages, and ranges of applicability. The measure of a unique technique, however, is that it must have important advantages specific to itself. One of the specific advantages of optical tweezers is the range of optical spring constants available. Tweezers can typically measure forces weaker by far than either needles or AFM. Force constants as low as 0.04 pN/nm have been reported [16]. Furthermore, its optical spring constant is rapidly and continuously adjustable. Overall, it is a better match to the forces of molecular motion than needles or AFM. It is quite simple and can manipulate single particles just by moving a single laser beam. The microneedles technique has the advantage of generating high force with little compliance, but it is much more difficult experimentally and less adaptable to rapid feedback control. Optical tweezers lack the spatial resolution of AFM, although resolution of a fraction of a nm is possible, which is sufficient to resolve the stepping distances of single motor molecules and the stepping of mechano-enzymes over DNA with single-base-pair resolution. See Chapter 8.

The ability to use optical tweezers to manipulate particles and organelles deep within living cells [17]*, [18], even underneath cell structure, as in confocal microscopy, is quite unique [19]*. This latter ability stems from the high numerical aperture of tweezer trapping light. It also involves use of infrared laser light to minimize optical damage to biological cells and particles [20]*, [21]*. Optical tweezers have provided a powerful new way of studying the mechanical properties of the cytoplasm. The elastic and viscoelastic properties of cell membranes and of the polymers making up the cytoskeleton of cells can be readily observed and measured [19]*, [22], [23]. Numerous studies of the elastic properties of long strands of DNA have also been carried out and they have given new information on the packing and unfolding of these complex molecules [22], [24], [25]. As we will see, measurements are even being made of the elastic compliance of parts of various motor molecules in order to understand their detailed functioning.

In physics, it is fair to say that trapping and cooling techniques have revolutionized large areas of experimental atomic physics.

Ashkin's proposal of stable optical trapping in 1970 [1]* and Hänsch and Schawlow's proposal to use molasses for optical cooling of atoms in 1973 [26]* led to the invention, in the late 1970s, of single-beam gradient traps cooled by molasses to the Doppler limit in the regime of hundreds of μK (see Chapters 3 and 4).

The final experimental achievement of cooling and trapping of atoms by Chu, Hollberg, Bjorkholm, Cable, and Ashkin [27]* in 1985 and by Chu, Bjorkholm, Ashkin and Cable [4]* in 1986 marks the beginning of the modern era of optical manipulation of ultracold atoms. Atomic vapors have since been cooled with the help of light to temperatures of about a nanokelvin, which is probably at present the lowest observed kinetic temperature in the universe. Such a low temperature corresponds to an atomic center of mass velocity of a fraction of a mm/s. For comparison, the recoil velocity of a sodium atom emitting just a single photon is about 3 cm/s (see Sec. 5.1 and Chapter 16). With atomic velocities as slow as mm/s one is dealing with atoms that are essentially at rest. Here, gravity becomes a major force. When such atoms are held in optical traps, the trapping forces balance the gravitational force and there are no serious difficulties. Such samples of slow atoms are close to the ultimate for Doppler-free spectroscopy. It is interesting to note that single-photon recoils, called the "Einstein *Rückstoß*", were first observed in 1933 (in pre-laser days) by Frisch [28], using a strongly apertured sodium atomic beam and a sodium lamp light source. It took the unique properties of lasers, however, to exploit these atomic recoils in a usable way.

One does not need such ultralow sub-recoil temperatures for many of the practical applications of optical manipulation of atoms, such as experiments on atomic fountains, atomic clocks, studies of atom–atom collisions, atomic interferometers, atomic gravity measuring devices, atomic lithography, and other so-called atom optics uses. To achieve Bose–Einstein Condensation (BEC), however, does require ultra low atom temperatures; to observe BEC one must also reach a critical phase–space density that depends on temperature and particle density.

The BEC was first successfully achieved in 1995 by Anderson, Ensher, Matthews, Wieman, and Cornell [29]* and by Davis, Mewes, Andrews, van Druten, Durfee, Kurn and Ketterle [30]*, using evaporative cooling of atoms from magnetic traps. This was followed closely thereafter by observation of primitive forms of pulsed atom lasers [31]*, [32], [33]*, [34]*. A difficulty associated with these

early atom lasers was the low intensity of coherent atoms and the pulsed nature of the output. These lasers need more particles for further observations and for many practical applications. Evaporation as currently practiced results in the loss of 90–98.5% of all the original atoms! Proposals have recently been made for achieving true continuous wave (cw) atom laser operation based on optical dipole traps (see Sec. 20.19). In addition to condensing bosons into a BE condensate, it has also been shown, in 1999, that fermions could be cooled to temperatures below their threshold for condensation into a degenerate gas [35]* and into the regime where fermion pairing occurs. See Chapter 25.

At present there are literally thousands of papers and dozens of review articles and reprint volumes on various aspects of the overall subject of optical trapping, cooling, and manipulation of neutral particles. A Nobel Prize in physics was awarded jointly to Chu, Cohen-Tannoudji, and Phillips in 1997 “for development of methods to cool and trap atoms with laser light” [36], [37], [38]. Another Nobel Prize in physics was awarded in 2001 jointly to Cornell, Ketterle, and Wieman “for the achievement of BEC in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates” [39]. With a history extending over 30 years, one might reasonably ask, why yet another review and reprint volume such as this one? The answer is that the present book will be substantially different from the previous reviews and books by others, because none of these earlier reviews treats the entire subject of optical manipulation of neutral matter as a single coherent subject. The reviews have become so specialized that readers have barely even been made aware of the existence of other related subfields of the overall subject. To mention just a few, I note the following:

- (i) “Trapping of Neutral Atoms”, edited by N. R. Newbury and C. Wieman [40] is a reprint volume (Resource Letter TNA-1) published by the American Association of Physics Teachers (AAPT), intended as a guide for university physicists and astronomers, and as a teaching aid. This tutorial volume discusses essentially only the trapping and cooling of atoms. As explained by Newbury and Wieman on p. 18, the review specifically limits its considerations to independent atoms. It mentions two types of neutral atom traps, the dipole or gradient trap, and the spontaneous force trap. As they further point out, principal emphasis is on the so-called Magneto-Optical Trap (MOT) or spontaneous force trap. It should be stressed that the MOT is *not* an all-optical trap, because it is a MOT. There is, therefore, scant information in this resource letter on the origin of all-optical trapping or the developments leading to the use of all-optical trapping in the rest of physics, chemistry, and the biological sciences.
- (ii) C. Cohen-Tannoudji and W. D. Phillips, “New Mechanisms of Laser Cooling” [41] is a review article narrowly restricted to the problems of atom cooling, starting with the Hänsch and Schawlow paper in 1975 [26]*.
- (iii) “Ultracold atoms and BEC”, Volume VII of Trends in Optics and Photonics (TOPS), edited by Keith Burnett, featuring papers from EQEC '96 (the European Quantum Electronics Conference September 8–13, 1996, Hamburg, Germany), published by the Optical Society of America. This volume primarily treats cooling atoms to ultracold temperatures and BEC. Practitioners of BEC essentially consider BEC to be an independent field, separate from laser cooling and trapping of neutral atoms. Even Physical Review Letters for quite a while put papers on BEC in the “General Physics” category, separate from the “Atomic Physics” category. This TOPS review is thus quite restricted in subject matter.

- (iv) Koen Visscher and Steven M. Block, “Versatile Optical Traps with Feedback Control” [42], is a review that focuses primarily on the use of optical tweezers and the newly developed feedback control method in biology for measuring the detailed forces and stepping motion of the motor molecule kinesin. The dynamics of other single molecular motors and the so-called mechano-enzymes are also considered, but practically little else.
- (v) “Laser Tweezers in Biology”, in *Methods of Cell Biology*, Vol. 55, edited by Michael P. Sheetz, Academic Press, New York, 1998. The subject matter of the articles in this book is restricted to the use of optical tweezers in biology.

As can be seen from the above five examples, the subject of laser trapping and manipulation of neutral particles has become so fragmented that the overall coherence and perspective that existed earlier in the field is almost completely lost. Nowhere in these reviews is made clear the intimate interrelationship between the forces on small macroscopic dielectric particles and biological particles, and the forces on atoms and BE condensates. Indeed, the fact that *the basic optical trapping principles and manipulative techniques closely apply for all particle types* has, over time, become blurred or forgotten. Also lost in this process of specialization and concentration on specific applications is the basic simplicity of the subject.

The thrust of the present book is therefore to present the subject in its simplest form, with emphasis on the origins of the subject and a basic understanding of the physical principles at work. A beautiful aspect of the subject is that simple optical principles (such as ray optics, Fresnel reflection and refraction), an elementary semi-classical view of the atom, and a description of optical forces based on the conservation of momentum are sufficient for an understanding of most of what we now know about optical trapping, cooling, and manipulation of small neutral particles.

Indeed, it was only by resorting to such elementary, simplistic concepts, with the help of simple experiments, physical intuition, and a little luck, that it became possible for Ashkin and collaborators to discover optical traps and optical manipulation in the first place [1]*, [2]*, [3]*, [20]*, [43]*.

One may rightfully ask, for whom is this book written? My answer is that it is written primarily for intelligent college seniors or starting graduate students interested in learning about optical traps and optical manipulation of particles. Because very few practitioners or young students of this subject may have read or have ready access to the early (mostly 25- or 35-year-old) papers, most of them probably know very little about the origins of the field and its relation to the subfields. I also hope that professional scientists and historians of science working in this field will benefit from this book, as well.

Knowing the origin of the field and knowing the interconnection between different parts of the overall field allows one to apply what was learned in one area to others areas. What was considered of only marginal interest in the early work on trapping forces and manipulation of micrometer-sized dielectric spheres [1]*, in time led to the understanding of the optical forces on atoms [3]*, to the invention of optical tweezers [3]*, and to the demonstration of atom cooling and trapping [4]*, [27]*. The discovery of atom trapping and cooling work led quite directly to BE condensation [29]*, [30]*, fermion condensation [35]* and later to the atom laser [31]*, [32], [33]*, [34]* (see also the recent work in Chapter 20). The invention of optical tweezers gave rise to the technique of damage-free trapping of biological particles by Ashkin and Dziedzic [44]*. This technique, in turn, led to the

manipulation of single live cells and single molecules, and studies of the mechanical properties of cells, as originally shown by Ashkin and Dziedzic [19]*.

For the most part, the book is organized chronologically. This helps one to follow the development of the subject as it actually happened. It also helps to separate good ideas from bad, since some ideas that were considered impractical or even wrong when originally proposed can later, in new contexts, be modified and made to work. Conversely, ideas and techniques originally touted to be essential have proven to be limiting and in need of replacement. Although there is no serious attempt on my part to be encyclopedic or complete, most of the important papers in the field up to the year 2005 will be alluded to, if only briefly.

General questions about the possibility of trapping neutral particles using radiation pressure forces will be addressed in the context of the much misunderstood Optical Earnshaw Theorem [45]*. The relationship of the Optical Earnshaw Theorem and the conventional Electrostatic Earnshaw Theorem to the trapping of other particles, such as electrons, ions, and neutrons, using other forces, will be clarified. Questions of AC (alternating force) versus DC (cw force) traps will be considered for optical traps, partly optical traps, ion traps, magnetic traps, and other types of traps. The question of the conservative and nonconservative nature of the optical and other trapping forces also will be discussed. This review as outlined above should help to place *optical traps* in overall context with other types of particle traps.

The author feels he writes this review volume from a privileged perspective. In 1970, he discovered optical trapping of neutral particles and also proposed optical trapping of atoms [1]*. In 1978 he discovered how to maximize the forces of radiation pressure on atoms and invented the single-beam gradient trap (now known as “optical tweezers”) [3]*; at that time he also developed the concept of cold light, which plays such a big role in BE condensates. His collaboration with Chu, Bjorkholm, Hollberg, and Cable resulted in the first demonstration of optical molasses in 1985 [27]* and the first optical trapping of atoms in 1986 [4]*. In 1987, with Dziedzic and Yamane, he discovered the infrared optical tweezer trap [20]*, and initiated the use of laser trapping in biology. He has followed subsequent developments in optical trapping and manipulation closely and with great interest [8], [9], [10]*, and as recently as 2004 proposed ideas for a viable optical cw atom laser [46]*.