Optical Trapping and Manipulation of Small Particles by Laser Light Pressure

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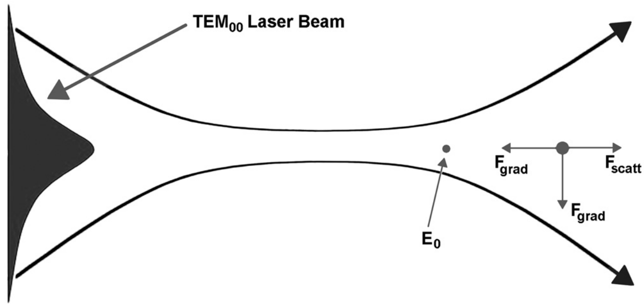
The invention of the laser has made possible the use of radiation pressure to optically trap and manipulate small particles. The particles can range in size from tens of micrometers to individual atoms and molecules. Laser radiation pressure has also been used to cool atoms to exceptionally low temperatures, enabling a new branch of atomic physics. See [1] for an extensive summary of the many varieties of work done with laser radiation pressure.

Inspired by a long interest in radiation pressure, in 1969 the author focused a TEM_{00} mode laser beam of about 30-μm diameter on a 20-μm transparent dielectric latex particle suspended in water. Strong motion in the direction of the incident light was observed. If the particle was off axis, at the edge of the beam, a strong gradient force component to the light force pulling the particle into the high-intensity region on the axis was observed. The particle motion was closely described by these two force components: one called the "scattering force" in the direction of the incident light and the other the "gradient force" in the direction of the intensity gradient. With these two components, and using two oppositely directed beams of equal intensity, it was possible to devise a stable three-dimensional all-optical trap for confining small particles. Particles moving about by Brownian motion that entered the fringes of the beam were drawn into the beams, moved to the equilibrium point, and were stably trapped. If the axial gradient force is made to exceed the scattering force, and this can be done, then a single-beam trap is possible, as shown in Fig. 1.

Because this was the first example of stable optical trapping, this discovery was submitted to *Physical Review Letters*. Since single atoms are just small neutral particles and should behave much as single dielectric spheres, it was postulated that trapping of single atoms and molecules should also be possible. At Bell Labs, if one wanted to submit a paper to *Physical Review Letters* one had to pass an internal review by the prestigious theoretical physics department to preserve the Lab's good name. So the author submitted a manuscript and it was rejected. Upon the recommendation of his boss, Rudi Kompfner, the inventor of the traveling-wave tube, the paper was resubmitted and was accepted with no problem [2]. A second theoretical paper was submitted to *Physical Review Letters* in 1970 on acceleration, deceleration, and deflection of atomic beams by resonance radiation pressure [3]. This was followed by a number of experiments on optical traps for micrometer-size solid spheres or liquid drops demonstrating optical levitation against gravity in air and as a function of pressure down to high vacuum and for various beam convergence angles. By using optical levitation in conjunction with feedback stabilization of the levitated particle's position, it was possible to study the wavelength dependence of the optical levitation forces with dye lasers. A series of complex size-dependent resonances were observed that were found to be in close agreement with Mie–Debye electromagnetic theory calculations. These results are probably the most exact confirmation of Maxwell's theory for light scattering by transparent dielectric spheres. The frequencies of these resonances allow one to determine the particle size and index of refraction to six or seven significant figures. Using the position stabilization technique it was possible to perform a modern



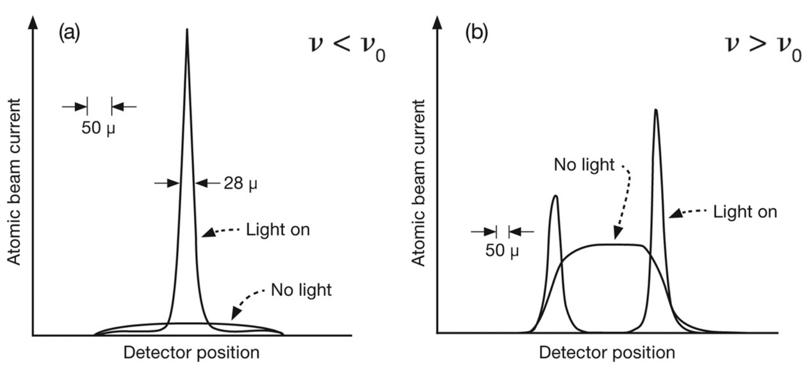
▲ **Fig. 1.** A single-beam optical trap for a high-index, transparent sphere. The laser beam is tightly focused such that the axial component of the gradient force exceeds the scattering force. E_0 is the equilibrium point at which the sphere is trapped.

version of the Millikan oil drop experiment for accurately determining the electric charge of a single electron.

Optical trapping of atomic vapors in high vacuum is more difficult than trapping macroscopic particles. One needs some form of damping for filling and holding atoms in an optical trap. Work was started in the early 1970s on accelerating, decelerating, and deflecting atoms with applications such as velocity sorting and isotope separation. T. Hänsch and A. Schawlow wrote an important early paper on optical cooling of atoms using the Doppler shift in a six-beam geometry for use in precision spectroscopy. They did not consider the possibility of optical trapping. In Russia, V. S. Letokhov and V. G. Minogen did experiments trying to stop sodium beams with chirped counterpropagating light beams, but failed. They were intending to trap atoms in a trap tuned a half-linewidth below resonance where cooling is a maximum. W. D. Phillips and H. W. Metcalf, inspired by Ashkin's first paper about atoms, also started work on atom slowing. They soon realized that the slowing difficulties experienced by Letokhov and Minogen were due to optical pumping, and in 1982 they successfully used a beam-slowing method based on a tapered magnetic field to completely stop the beam at a final temperature of about 0.1 K.

In 1978 Bjorkholm, Freeman, and the author carried out an experiment using tuning far from resonance that demonstrated dramatic focusing and defocusing of an atomic beam caused by the optical gradient forces [4] (Fig. 2). These striking results suggested that atom trapping would be possible if proper cooling could be achieved. It was realized that optical heating of atoms was a problem in achieving stable traps for cold atoms even for optimal tuning at a half-linewidth below resonance, where the cooling rate is a maximum, due to saturation. However, it was shown that deep trapping potentials were possible for two-beam traps and one-beam traps by tuning far-off resonance where saturation is greatly reduced. Two papers by Ashkin and Gordon addressed the details of laser cooling and heating and showed various ways of achieving adequate Doppler cooling.

In 1983 Steve Chu was transferred to our Holmdel Lab from the Murray Hill Lab. He was an experienced atomic physicist, but he did not know much about trapping at the time. He became interested and decided to join John Bjorkholm and the author in an attempt to trap atoms using lasers. This was at a time when we had some new bosses who decided that atom trapping would not work, and they tried unsuccessfully to discourage Bjorkholm and Chu from working with the author on this project. In spite of this pressure, Chu was given a quick lesson in atom trapping, and an effort was made to demonstrate the first optical trap for atoms. The first experiment was aimed at creating a collection of



◀ **Fig. 2.** Experimental demonstration of the focusing and defocusing of an atomic beam caused by the optical gradient force. (a) Laser tuned below resonance; atoms attracted to high intensity regions. (b) Laser tuned above resonance; atoms repelled from high intensity regions. (Redrawn from A. Ashkin, [IEEE J. Sel. Topics Quantum Electron. **6**(6), Nov./Dec., 2000.])

very cold atoms capable of being confined in the shallow atom traps. The experiment was based on the theoretical ideas proposed by Hänsch and Schawlow, mentioned earlier, and it worked beautifully. It provided a cloud of atoms having a temperature of about 240 μK, as expected, which is ideal for trapping. That cooling technique has become to be known as "optical molasses." Now that it was possible to generate cold atoms, Bjorkholm suggested trying a single-beam gradient trap in spite of its small size. The trap worked flawlessly, and shortly afterward, in December 1986, the work was featured on the front page of the Sunday *New York Times*. Surprisingly, a new trapping proposal by Dave Pritchard of MIT appeared in the same issue of *Physical Review Letters* as our trapping paper. It was for a large-volume magneto-optic scattering-force trap rendered stable via a quadrupole Zeeman-shifting magnetic field. The magneto-optical trap (MOT) is a relatively deep trap and is easily filled because of its large size. As later shown, it did not even require any atomic beam slowing.

Shortly after the atom trapping experiment, Chu left Bell Labs for Stanford and continued his atom trapping work. At Bell Labs, Bjorkholm and Ashkin turned to other work. Use of MOT traps dominated over dipole traps for atom work for about the next ten years. In 1997 the Nobel Prize in Physics was awarded to Chu, Phillips, and Cohen-Tannoudji for cooling and trapping of atoms.

In the lab, with the help of Joe Dziedzic, the author started looking at the use of focused laser beams as tweezers for the trapping and manipulation of Rayleigh particles. They made a surprising discovery one morning when while examining a sample that had been kept in solution overnight. Wild scattering was seen emanating from the focus of the trap. A joke was made about having caught some bugs. On closer examination it turned out that that this had happened. Bacteria had contaminated the sample, and they had fallen into the trap. The sample was placed under a microscope where the trapping could be observed in detail. In fact, the trap could be maneuvered to chase, capture, and release fast-swimming bacteria with green argon-ion laser light. If the laser power was turned up, "opticution" was observed; that is, the cell exploded. It was found that infrared YAG laser power was very much less damaging. Samples of E. coli bacteria obtained from Tets Yamane of Murray Hill were seen to reproduce right in the trap. Internal-surgery was performed in which the location of organelles was rearranged and the organelles were attached in new locations. The visco-elasticity of living cell's cytoplasm and the elasticity of internal membranes were also studied. This early work was the start of a new, unexpected, and very important application of laser trapping. A Nobel Prize winner at Bell Labs mentioned, amusingly in retrospect, that the author "should not exaggerate" by predicting that trapping would someday be important for the biological sciences.

Meanwhile, work to better understand optical molasses cooling of atoms was carried out at NIST and Stanford. Importantly, at NIST Phillips had made the surprising discovery of cooling to temperatures as low as 40 μK in "optical molasses." This was of great interest to those racing to achieve Bose–Einstein condensation (BEC) at very low temperatures and high densities. Anderson *et al.* won this race in 1995 using evaporative cooling from a magnetic trap reaching a temperature of about 170 nK at a density of 2×10^{12} atoms/cm^3 with a loss of evaporated atoms by a factor of 500 from an original 10^7 atoms. Eric Cornell, Carl Weiman, and Wolfgang Ketterle received the 2001 Nobel Prize in Physics for the experimental demonstration of BEC.

The Nobel Committee in their 1997 press releases "Addendum B" on additional material mainly for physicists says "To become really useful one needed a trap deeper than the focused laser beam trap proposed by Letokhov and Ashkin and realized by Chu and coworkers in optical molasses experiments." On the contrary, far-off-resonance traps built according to Ashkin's design are the traps used in virtually every current Bose–Einstein experiment.

The story of the application of tweezer traps to biophysics and the biological sciences is more straightforward [5–7]. After the early work of the author on living cells, Ashkin and collaborators and Steven Block with Howard Berg showed the usefulness of optical tweezers for studying single motor molecules such as dynein, kinesin, and rotary flagella motors. Block and his co-workers continue to extend tweezer techniques to DNA replication and protein folding at even higher resolution (fractions of an angstrom) and lower force levels using super-steady optically levitated low-noise traps held in a helium gas environment.

Light-pressure forces are probably the smallest controllable and measurable forces in nature. Other low-force techniques such as atomic force microscopy (AFM) have their unique features but cannot function deep inside living cells, for example. Looking to the future, one expects the interesting work on motors and protein folding to continue. Perhaps we will see optical tweezers serving as gravitational wave detectors. Large improvements in atomic clocks have been made in the past using atomic fountain techniques. Recently another breakthrough has been made using ultracold optical lattice clocks approaching a stability of one part in 10^{18}. This achievement in time keeping by NIST has many potential applications.

The study of light is fundamental to physics. As such, one expects that applications of optical trapping and manipulation of particles by laser light pressure will continue well into the future.

The importance of using lasers for the trapping and cooling of atoms has been recognized by a number of prizes and awards, including the Nobel Prizes mentioned above. In addition, Arthur Ashkin has been recognized for his work in that field by The Optical Society (OSA) with the Charles H. Townes award in 1988, with the Ives Medal/Quinn Award in 1998, and by being elected an Honorary Member of OSA in 2010.

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