Laser Manipulation of Atoms and Particles

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A variety of powerful techniques to control the position and velocity of neutral particles has been developed. As examples of this new ability, lasers have been used to construct a variety of traps, to cool atoms to temperatures below 3×10^{-6} kelvin, and to create atomic fountains that may give us a hundredfold increase in the accuracy of atomic clocks. Bacteria can be held with laser traps while they are being viewed in an optical microscope, and organelles within a cell can be manipulated without puncturing the cell wall. Single molecules of DNA can now be stretched out and pinned down in a water solution with optical traps. These new capabilities may soon be applied to a wide variety of scientific questions as diverse as precision measurements of fundamental symmetries in physics and the study of biochemistry on a single molecule basis.

THE ABILITY TO CONTROL THE POSITION AND VELOCITY OF isolated atoms and microscopic particles has dramatically improved in the last several years. In particular, researchers can now use electromagnetic fields to remotely manipulate neutral particles with unprecedented control. In this article I will review some of the highlights in neutral particle manipulation with emphasis on the most recent work. Several previous reviews written for the general audience have given accounts of the earlier work (*1*). More technical reviews and monographs (*2*), and collections of original work (*3*), have also been published. The spectacular successes with ion trapping have also been reviewed (*4, 5*) and will not be discussed in this article.

Light Forces, Laser Cooling, and Optical Molasses

Light can exert forces on an atom because photons carry momentum. The exchange of photon momentum with an atom can occur incoherently, as in the absorption and reemission of photons, or coherently, as in the redistribution (or lensing) of the incident field by the atom. The two kinds of forces can also be viewed as the interaction of the light with the imaginary and real part of the index of refraction associated with the atom.

The force arising from the coherent interaction with light is also called the dipole force. The laser field polarizes the atom, and the polarized atom experiences a force in the gradient of an electromagnetic field. Unfortunately, the dipole moments that can be induced on an atom are small, and the force is too feeble even to overcome random thermal motion at room temperature. Many of the successes of atom manipulation have occurred not because lasers can exert powerful forces on atoms but because techniques have been found to cool these particles to low temperatures while still in the vapor phase. Once the atoms are cooled to temperatures on the order of 1 millikelvin, the electric and magnetic dipole forces can easily overcome thermal motion, and these feeble forces become sufficient to control the atoms. Laser cooling was a key preliminary step in the wide variety of trapping and manipulation techniques that have been developed within the last few years.

The incoherent interaction that can alter the momentum of an atom is also called the "scattering force" because it arises from direct photon scattering events. Every time an atom scatters a photon carrying momentum $p = h/\lambda$ (h is Planck's constant and λ is the wavelength of light), the atom experiences a small change in velocity. In the case of incoherent scattering, two momentum impulses are delivered to the atom: one along the direction of the incident photon and another opposite the direction of the scattered photon. Because the photons are not scattered into a preferred direction, the net average velocity change per scattered photon Δv is opposite the direction of the incident photons with $\Delta v = p/M = h/\lambda M$, where M is the mass of the atom. For sodium, $\Delta v = 3$ cm s^{-1} appears insignificant as compared to typical atomic thermal velocities of 6×10^4 cm s^{-1}. However, over 10^7 photons can be scattered per second, and the light force experienced by the atom can be thousands of times larger than the gravitational force the earth exerts on the atom. In 1985, National Bureau of Standards (NBS) groups at Gaithersburg, Maryland, and Boulder, Colorado (*6*), cooled atoms in a thermal (starting with a velocity width equivalent to ~300 K) atomic beam to 50 to 100 mK by irradiating them with a beam counterpropagating against their motion.

A substantial improvement in laser cooling was achieved with the use of counterpropagating laser beams. If the laser is tuned to the low-frequency side of an atomic resonance, an atom moving against the direction of a laser beam will see the beam Doppler-shifted into resonance, while the beam copropagating with the atom will be Doppler-shifted out of resonance. Thus, the atom will preferentially scatter photons from the beam opposing the direction of motion. Cooling in three dimensions is accomplished by creating three sets of counterpropagating beams along the x, y, and z axes. Two of the advantages of using three sets of counterpropagating beams over a single beam are that the method does not depend on a knowledge of the direction of motion of the atom, and there is no heating of the atoms along the directions transverse to any one set of counterpropagating laser beams. The idea was suggested by Hänsch and Schawlow in 1975 (*7*) and first demonstrated in 1985 by Chu and his colleagues at AT&T Bell Laboratories (*8*). Because the cooling force is viscous (linearly proportional to the velocity of the atom for low velocities), we named the laser beams that generate the drag force "optical molasses."

In addition to cooling the atoms, the experiment also demonstrated that the optical molasses serves as a confining medium. An atom

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caught in molasses will execute a random walk analogous to the Brownian motion of a dust particle in a fluid. The equilibrium temperature of the atom results from the competition between the cooling forces on the atom and the continual random scattering of photons that heat up the atom in the absence of the cooling force. On the basis of these simple considerations, the minimum equilibrium temperature of the atom is calculated to be on the order of $k_BT = \hbar\Gamma/2$ (*9*), where Γ is the width of the absorption line, $\hbar$ is $h/2\pi$, and k_B is the Boltzmann constant. The calculated confinement time for an atom in a region of optical molasses defined by beams 1 cm in diameter would be on the order of seconds (*8*). A more complete quantum mechanical treatment of the cooling and heating forces for an idealized two-level atom consisting of a ground state and an excited state showed that the simple estimates were correct in the limit of low-intensity light (*2, 10*).

The first optical molasses experiments (*8, 11*) seemed to confirm the theoretical expectations. However, the tidy picture soon began to unravel. The group at Bell Laboratories realized that the temperature was too low for the intensities used in the original experiment. Also, the storage time of the atoms could be increased by as much as a factor of 50 if the beams were misaligned in particular ways (*12*). This so-called "supermolasses" collects the atoms into what may be a light trap, but its mechanism remains a mystery. In 1987, the National Institute of Standards and Technology (NIST) (formerly NBS) group in Gaithersburg began to discover other discrepancies. For example, they found that the storage time of atoms in molasses was less sensitive to the intensity imbalance of the counterpropagating beams than predicted (*13*).

The most startling surprise, discovered by the NIST group in 1988 (*14*), was that atoms could be cooled to temperatures more than an order of magnitude lower than the limit expected from cooling with the Doppler effect provided that the stray magnetic fields on the atoms were reduced to tens of milligauss and the laser was tuned several linewidths below resonance. By comparison, the two-level theory predicts that the temperature would be a minimum at a detuning of $\Gamma/2$, where the differential absorption between conterpropagating laser beams is a maximum in the limit of low laser intensity. In virtually all respects, the optical cooling of atoms has worked far better than anticipated; the work is a rare but spectacular violation of Murphy's law.

Cooling Multilevel Atoms with Polarization Gradients

Several months after the NIST group announced their findings, Dalibard and Cohen-Tannoudji at the Ecole Normale Supérieure (*15*) and Chu *et al.* (*16*) offered an explanation of the colder temperatures based on a new cooling mechanism. These models were later refined and extended by the two groups in subsequent publications (*17, 18*), and a popular review of new mechanisms for laser cooling has recently been published (*19*). The cooling mechanism depends on effects known as optical pumping, light shifts, and the motion of atoms in light fields with polarization gradients. Although many of these properties have been exploited in earlier laser cooling techniques, the effects due to a combination of these properties had to await experimental discovery.

To see how these effects conspire to cool atoms, consider an atom with magnetic sublevels moving in a laser field composed of two orthogonally polarized counterpropagating beams (Fig. 1A). The resulting field has polarization gradients because the local polarization changes from positive helicity (where each photon of the light carries $+\hbar$ unit of angular momentum) to linear to negative helicity ($-\hbar$ angular momentum).

An atom in a region of positive helicity will have its ground-state population redistributed (optically pumped) after repeated absorption and spontaneous emission of photons. For example, in Fig. 1B an atom with two sublevels of the ground state (angular momentum $F = 1/2$, $m_F = +1/2$ and $-1/2$ in units of $\hbar$) will optically pump into the $+1/2$ level. The laser field also shifts the energy levels of the atom (the light shift); if the laser is tuned below the resonant frequency of the atom, the energy of the ground states shifts to lower energy by an amount proportional to the transition probability. Thus, the atom optically pumps into the ground state with the largest light shift (*20*).

Consider an atom in the positive helicity region that has been optically pumped into the $+1/2$ ground state. If it moves into the negative helicity region in a time comparable to the optical pumping time, the atom has a good chance of remaining in the $+1/2$ state. However, the light shift of the $+1/2$ state is now one-third of what it was in the region of positive helicity. Thus, the internal energy of the atom has increased, and this increase is balanced by a decrease in the kinetic energy. The increased internal energy is dissipated by the spontaneously emitted photons during the continuous optical pumping process. Under low excitation conditions, the optical pumping time can be comparable to the time it takes an atom moving at speeds of a few centimeters per second to go a distance $\lambda/4$ to a region of new polarization.

Computer simulations by both the Stanford and the Ecole Normale groups showed that the atoms should cool to an effective temperature corresponding to a few photon recoil momenta (*17, 18*). At these low temperatures, the de Broglie wavelength of the atom $\lambda = h/p$ is comparable to the distance scale of the polarization gradients. The first theoretical work treated the coordinates of the atom classically, but at the lowest obtainable temperatures the wave-like nature of the atom must be considered. A recent full quantum mechanical treatment shows that the minimum temperature in one dimension is equivalent to ~5.5 photon momenta for an $F = 1/2$ ground state and an $F = 3/2$ excited state (*21*). A method for calculating forces on atoms in laser fields in two and three dimensions has been outlined (*22*), but a complete theoretical analysis of two- or three-dimensional polarization gradient

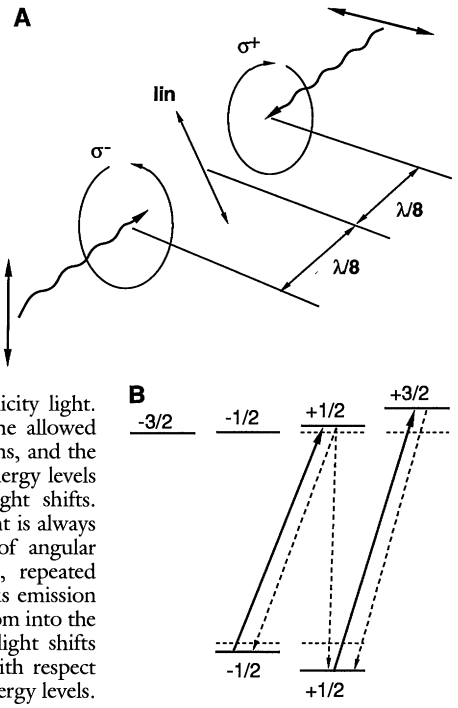

Fig. 1. (**A**) Polarization gradients that result from the superposition of orthogonal linearly polarized light. The local polarization of the light changes from positive helicity (σ^+) to linear (lin) to negative helicity polarization (σ^+) in a distance $\lambda/4$. (**B**) The energy levels of an atom with an $F = 1/2$ ground state and an $F = 3/2$ excited state irradiated with positive helicity light. The dashed lines show the allowed spontaneous emission paths, and the dotted lines denote the energy levels in the absence of the light shifts. Because the excitation light is always trying to add $+\hbar$ unit of angular momentum to the atom, repeated excitation and spontaneous emission will optically pump the atom into the $+1/2$ ground state. The light shifts are greatly exaggerated with respect to the separation of the energy levels.

cooling and heating has yet to be done.

Experimentally, sodium has been cooled in three dimensions to a temperature of ~30 μK (*14, 23*) corresponding to a thermal velocity of 3.5 photon momenta. In the case of cesium, the recoil velocity of each photon is only 0.35 cm s^{-1} and temperatures as low as 2.5 μK (also 3.5 photon momenta) have been reached (*24*). One-dimensional experiments in sodium show that the equilibrium velocity distribution is not thermal but consists of a cold distribution of atoms with an effective temperature of ~20 to 25 μK and a hot distribution with an effective temperature of 1 to 2 mK (*25*). The cause of the bimodal speed distribution is qualitatively understood (*18, 25, 26*), but, because theory has not yet included the effects of more than one set of hyperfine levels (sodium has two ground state hyperfine levels), a quantitative comparison of the sodium data with theory cannot be made.

There are other forms of sub-Doppler cooling that have been recently identified. Dalibard and Cohen-Tannoudji described another cooling mechanism that arises in a field that is generated with counterpropagating laser beams of opposite helicity (*17*). They showed that an atom slowly moving in such a field optically pumps into a set of ground states that causes the atom to preferentially scatter more photons from the beam opposing its velocity. The Stanford group and subsequently a group from Stony Brook have shown experimentally and theoretically that a corollary to the polarization gradient cooling theory allows one to cool atoms one dimension below the Doppler limit in the absence of polarization gradients (*18, 25, 27*).

Temperatures Below the Photon Recoil Limit

If the so-called Doppler limit to laser cooling is not a limit, what are the fundamental limits to laser cooling? One might think that the limit would be the recoil limit $k_B T \approx p^2/2M$ due to the recoil of a single scattered photon, but even this barrier can be circumvented. For example, an ion tightly held in a trap can use the mass of the trap to absorb the recoil momentum. The so-called sideband cooling scheme proposed by Dehmelt (*5*) and Wineland and his colleagues (*4*) and demonstrated by Wineland and collaborators (*28*) uses this fact.

For free atoms, it is still possible to create an ensemble of atoms with a velocity spread less than the photon recoil velocity by using velocity selection techniques. The Ecole Normale group devised a clever velocity selection scheme based on a process they labeled "coherent population trapping." In this process, atoms are optically pumped in velocity space in order to increase the density of atoms in a velocity-selected state. They went on to demonstrate the idea by cooling one dimension of the transverse velocity of a metastable beam of helium atoms to 2 μK, a factor of 2 below the single photon recoil temperature (*29, 30*). The effective temperature of the velocity-selected atoms is expected to decrease roughly as the square root of the time that the velocity selection light is on, so much colder temperatures may be achieved if the atoms are cooled in optical molasses. More recently, population trapping schemes for cooling in two and three dimensions have been suggested (*29, 31*).

The Stanford group recently demonstrated a velocity selection scheme that has produced an ensemble of sodium atoms with a transverse velocity spread of 270 μm s^{-1}, corresponding to an effective temperature of 24 pK and a de Broglie wavelength of 50 μm (*32*). (Unlike coherent population trapping, this technique does not increase the number of atoms within a given velocity spread.) The velocity selection begins with a sample of atoms optically pumped into one of the ground-state hyperfine levels. The atoms are then irradiated with counterpropagating beams of light at ν_1 and ν_2 (Fig. 2) in order to induce a so-called Raman transition to the other hyperfine level. The atoms excited into the other state have a velocity spread given by the usual Doppler shift formula $\Delta\nu/c = \Delta\nu/\nu$, where ν is the sum of the two optical frequencies $\nu_1 + \nu_2$, c is the speed of light, and $\Delta\nu \approx 1/\Delta t$ is the inverse of the measurement time as dictated by the Heisenberg uncertainty principle. The stability of the laser is not crucial because the transition depends on $\nu_1 - \nu_2 \approx \Delta\nu_{hfs}$ (hfs is hyperfine structure), which is set by a stable microwave source driving an electro-optic modulator. The extreme velocity selection is possible because of the long measurement time and because the laser beams are configured to make the transition Doppler-sensitive instead of Doppler-free. By cycling optical molasses with a velocity selection technique, it should be possible to use velocity selection as a Maxwell demon to place most of the 3 μK atoms into the velocity-selected state (*33*).

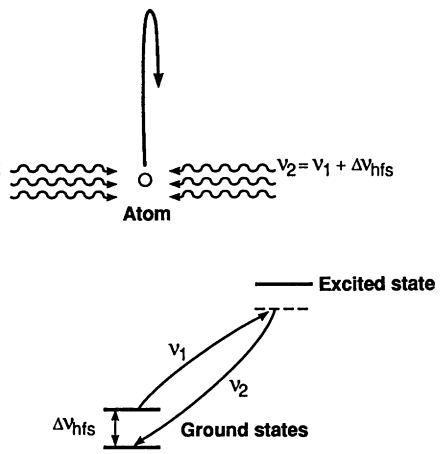

Fig. 2. Velocity selection of a narrow portion of the "hot" (several microkelvin) thermal distribution by a Doppler-sensitive Raman transition between the ground-state hyperfine levels. Because of the Doppler shifts of the two beams, only atoms within a narrow range of velocities (velocity along the direction of the laser beams) will be in resonance with the Raman transition for a given frequency difference $\nu_1 - \nu_2$ very close to $\Delta\nu_{hfs}$. The linewidth of the transition is determined by the transit time of the slowly moving atoms through the velocity-selecting laser beams.

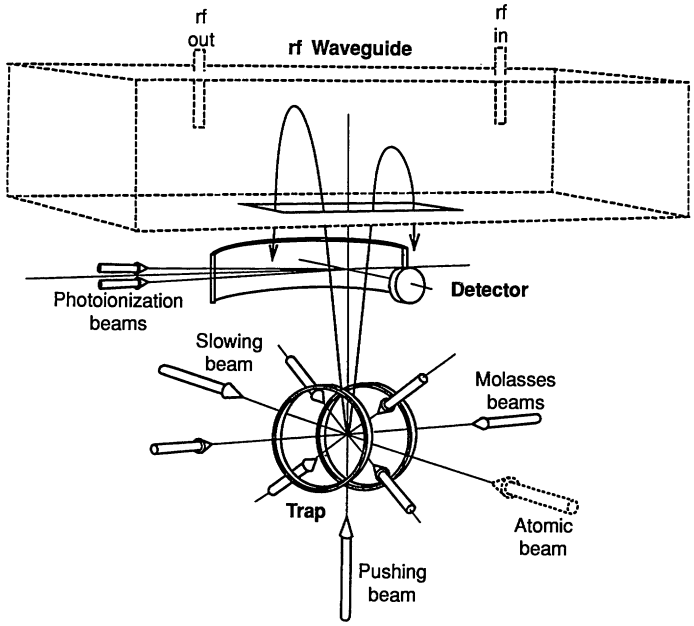

Fig. 3. Schematic diagram of the atomic fountain showing the loading of the magneto-optic trap from a conventional atomic beam, the ballistic trajectory of the cooled atoms through the radio frequency (rf) waveguide, and the resonant photoionization detection region. A resonance 2 Hz wide was demonstrated with this apparatus.[Adapted from (*37*)]

Neutral Atom Manipulation

In addition to cooling atoms to very low temperatures, there has been rapid progress in developing techniques to trap and otherwise manipulate neutral atoms. Magnetic traps (*34*), optical traps (*35*), and magneto-optic traps (*36*) have been demonstrated and used in a variety of applications. All of these traps work by strongly perturbing the energy levels of the atoms in a spatially dependent manner. In applications such as high-resolution spectroscopy one would like to avoid the trapping perturbations, and one solution is to work with freely falling atoms in slow atomic beams.

An extreme limit of a slow beam is an "atomic fountain" in which the atoms directed upward will return as a result of gravity. Zacharias first attempted to build an atomic fountain in the early 1950s, but the first successful demonstration had to await the advent of slow atom technology. The Stanford group has constructed an atomic fountain (*37*) by first trapping atoms from a thermal beam in a magneto-optic trap (*36*) and then pushing the atoms upward with a pulse of light from a continuous-wave laser as shown in Fig. 3. Near the top of the atomic trajectory, transitions between the ground-state hyperfine levels were induced by means of the Ramsey method of separated oscillatory fields (*38*). A measurement time of 0.25 s (the time between the two microwave pulses used to induce the transition) yielded a linewidth of 2 Hz, and after 15 min of integration time the center of the line could be resolved to 10 mHz.

The precision of a spectroscopic measurement depends on both the high Q (Q is the quality factor of the resonance defined by $Q = \nu/\Delta\nu$) and the signal-to-noise ratio of the signal. Thus, it is important to create a high-flux source of cold atoms. Also, many applications would benefit from a continuous beam of atoms instead of the pulsed source that was used in the first atomic fountain. Groups at Stanford and Bonn have developed an "atomic funnel," which produces a high flux beam of slow atoms that can be used in a continuous atomic fountain (*39*). The Stanford funnel accepts atoms with a large velocity spread and cools them into a localized and collimated beam. Because of the dissipative properties of optical molasses, the brightness of the atomic beam is not a conserved quantity as it would be for an optical beam. A figure of merit for an atomic beam is the peak phase space density defined to be the number of atoms per $\Delta v_x \Delta v_y \Delta v_z \Delta x \Delta y \Delta z$. With our funnel, a beam of atoms with a flux of 10^9 atoms per second at a velocity of 270 cm s^{-1} and a temperature of 200 μK was produced, corresponding to an increase in the phase space density by more than four orders of magnitude.

Other new techniques have recently been developed for neutral atom manipulation. Researchers have constructed grazing incidence atom mirrors (*40*) and normal incidence mirrors (atom trampolines) (*41*) by using an evanescent wave that extends out from a laser beam that is totally internally reflected inside a glass prism. Atomic diffraction gratings formed with both standing wave patterns of light (*42*) and matter gratings (*43*) have also been demonstrated. These devices may be useful as atom beam splitters and mirrors in the construction of atom interferometers.

Recently, the demonstration of an atom interferometer has been achieved by groups at Universität Konstanz (*44*), Physikalish-Technische Bundesanstalt (*45*), the Massachusetts Institute of Technology (*46*), and Stanford (*47*). In our work at Stanford, we have also demonstrated the extreme sensitivity of this device as an accelerometer. The acceleration of an atom due to gravity was measured with a resolution of 3 parts in 10^6, and we believe that another four orders of magnitude improvement should be possible.

Applications of Atom Manipulation Techniques

Laser cooling, trapping, and related techniques are finding applications in a number of areas. Because the experimental techniques have only recently blossomed, the full range of applications has not yet been realized.

An application that is receiving considerable attention is the construction of better time standards in the microwave or optical domain. A compact 8 cm high atomic fountain will increase the Q of the resonance by a factor of 13 over that of the 4 m long NBS VI atomic clock, and by a factor of more than 100 over that of the Hewlett-Packard 5016B cesium time standard. Most of the most troublesome systematic frequency shifts associated with a time standard will also be reduced as the velocity of the atoms is reduced. The short-term stability of the Hewlett-Packard commercial time standard with low noise option is $5 \times 10^{-12}/\sqrt{\text{Hz}}$, and that of the NBS VI clock is $2 \times 10^{-12}/\sqrt{\text{Hz}}$. Using cesium atoms collected in a magneto-optic trap, the Boulder group has achieved a short-term stability that would (in the absence of systematic effects) have an Allen variance equal to that of the Hewlett-Packard time standard (*48*).

The trapping technology has simplified to the point where practical laser-cooled atomic clocks are now possible. Wieman and collaborators have shown that cesium atoms can be cooled and trapped with diode lasers, most recently in a compact vapor cell with a magneto-optic trap (*49*). A cesium time standard based on a sealed cell design for which the cooling, manipulation, and detection of the atoms are all done with diode lasers should exceed the stability of the best present-day time standards. Time standards based on optical transitions and neutral atom fountains are also receiving a considerable amount of attention (*50*).

The fact that atoms can be laser-cooled and trapped in a sealed cell also means that experiments that require rare species of atoms such as rare isotopes can be optically manipulated. Measurements of parity nonconservation in a large number of isotopes of cesium or the creation of spin-polarized samples for β-decay studies might be possible (*51*).

A variety of precision measurements will benefit from the long measurement times possible with laser-cooled atoms. The most precise measurements are frequency measurements, and atomic physicists endeavor to cast their experiments as frequency measurements. Examples of precision measurements that can be transformed into frequency measurements of slowly moving atoms include the search for permanent electric dipole moments in atoms (a signature of a breakdown of time reversal symmetry), and an improved test of the charge neutrality of atoms (*52*).

The low temperatures now accessible with laser cooling allow one to study atomic collisions in a regime where the collision times become long enough to permit spontaneous emission during the collision. Thus, ground state–excited state collisions are significantly modified (*53*). Novel collision effects between ultracold atoms have already been studied (*54*). Radiation pressure from light reemitted by trapped atoms also exhibits dramatic mechanical effects. As more atoms are loaded into a magneto-optic trap, they are observed to suddenly burst from a roughly spherically symmetric shape to a ring or shell roughly centered around a core of atoms (*55*). Surface scattering experiments with submicrokelvin atoms have been used to measure the weak, long-range Casimir force and possible quantum reflections from an attractive potential well (*33*).

An ultracold gas of atoms should also display effects due to the quantum statistics of the gas. Differences in collision cross sections between fermions and bosons in low-temperature collisions are expected. When the de Broglie wavelength $\lambda = h/p$ of trapped atoms becomes comparable to the interatomic spacing, a Bose condensate or a degenerate Fermi gas should be formed depending on whether the total angular momentum of the atom is integer or half-integer.

Attempts to observe Bose condensation in a sample of magnetically trapped spin-aligned hydrogen (*56*) are in progress. Bose condensation of a cold gas of alkali atoms may also be possible.

Optical Tweezers and Applications to Biology

An optical trap based on a single focused laser beam, first suggested by Ashkin (*57*), works because the strong electric field of the laser beam is used to induce a dipole moment on the object being trapped. As long as the frequency of the laser field is below the natural resonances of the particle being trapped (for example, below the atomic transition of an atom or the absorption edge of a polystyrene sphere), the dipole moment is in phase with the driving electric field. Because the energy of the induced dipole **p** in the laser field **E** is given by $W = -\mathbf{p}\cdot\mathbf{E}$, the particle achieves a lower energy state by moving into the high-intensity focal spot of the laser beam. The trapping force this type of trap can exert on an atom is truely feeble, and the trap could not be experimentally realized until it was imbedded in an optical molasses medium that could cool atoms to below 1 mK (*35*).

In the case of small particles ranging from 10 μm down to ≈20 nm, the particles are polarizable enough so that water at room temperature can act as the substitute for optical molasses (*58*). Because the focal spot of the laser beam can be easily moved with mirrors or lenses, we dubbed the single focused laser beam trap "optical tweezers." The trapping of micrometer-sized particles is accomplished by directing the laser light through a microscope objective with a high numerical aperture so that the object can be simultaneously viewed and manipulated with the same objective.

An application of the optical tweezers that has captured the imagination of the biology community was the discovery by Ashkin and Dziedzic that bacteria can be moved about in a water solution without apparent damage to the organism (*59*). They went on to show that objects within a living cell such as organelles or filaments of cytoplasm can be manipulated while keeping the cell wall intact (*60*). Biologists have applied optical tweezers to a variety of problems. Measurements of the mechanical compliance of bacterial flagella (*61*) and the manipulation of sperm (*62*) and chromosomes in mitotic cells (*63*) have been demonstrated.

At Stanford, we have begun to manipulate single macroscopic molecules with optical tweezers. Even though biological molecules are too small to be trapped at room temperature, the molecule may be held if an appropriate "handle" is attached to the molecule. We have attached a polystyrene sphere to each end of a lambda phage DNA molecule via a biotin-strepavidin-biotin bridge (*64*). The manipulation of a single molecule has been seen in real time by a process in which the DNA is stained with ethidium bromide dye and the fluorescence is observed with an image-intensified video camera.

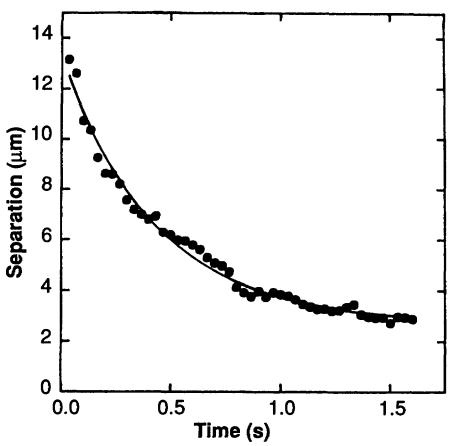

Fig. 4. The relaxation of a lambda DNA molecule in aqueous solution after it has been stretched out with a pair of laser traps. Each data point was taken from one frame (1/30th of a second) of a video picture. The solid line shows the expected behavior if the restoring force is linearly proportional to the distance between the beads. [Adapted from (*33*)]

The first measurements we made were on the elastic properties of DNA. Figure 4 shows the distance between two polystyrene spheres attached to the ends of a piece of DNA ~15 μm long as a function of the time. The spheres were pulled apart along the surface of a microscope slide in an aqueous solution with two independently controllable optical tweezers before one bead is released.

By leaving the laser beam focused on a bead impaled on the microscope slide for a few seconds, we found that the bead can be "spot-welded" to the microscope slide and the molecule can be left in its stretched state. Thus, the laser tweezers can be used as a means of preparing a sample for examination with a scanning tunneling microscope or an atomic force microscope. We hope to exploit our ability to manipulate and simultaneously observe single DNA molecules in the study of gene regulation, transcription, repair, and mapping.

Perhaps the most exciting applications in the field of laser cooling and trapping will come out of the ability to study problems in polymer physics and biology on a single molecular basis. Normally one examines the behavior of a large number of molecules, and the fundamental chemistry of the molecules must be inferred from the averaged behavior of the entire ensemble. On the other hand, the processes that govern the behavior of a single molecule are important: for example, the nucleus of a cell has a single molecular copy of its genetic blueprint, and its chemistry depends in part on the chemistry of single molecules. With the rapidly developing methods to label, observe, and manipulate single macroscopic molecules with a simple optical microscope, questions as diverse as the reptation of a single fluorescently labeled polymer within a sea of entangled polymers or the movement of a repair enzyme along the DNA chain can be addressed in a direct way. It is a personally gratifying example of the unity and synergism of science that seemingly esoteric work in atomic physics is having impact in chemistry and may give us new methods to study fundamental biological processes.

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Ex Situ Conservation of Plant Genetic Resources: Global Development and Environmental Concerns

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Conservation of plant genetic resources is achieved by protection of populations in nature (in situ) or by preservation of samples in gene banks (ex situ). The latter are essential for users of germplasm who need ready access. Ex situ conservation also acts as a back-up for certain segments of diversity that might otherwise be lost in nature and in human-dominated ecosystems. The two methods are complementary, yet better understanding of this interrelation and the role of ex situ conservation in global environmental considerations is needed. Inclusion of ex situ conservation efforts within current environmental policies conserving global diversity would focus greater international attention on the safeguarding of these efforts.

CONSERVATION OF PLANT DIVERSITY CAN BE ACHIEVED IN A number of complementary ways: conservation of whole plants in their native ecosystems or conservation of samples of a plant's genetic diversity and of endangered species. Frequently, one method acts as a back-up to another, and the degree of emphasis placed on a particular method depends on a specific strategy developed to fulfill conservation aims and uses.

Donor agencies have increasingly incorporated environmental considerations in international development activities of the past decade. When these considerations include conservation, support is generally provided for protection of plants in situ because of the urgent need to protect ecosystems in face of imminent change.

Conservation of samples of plants away from their field habitats is considered to be ex situ. This has been most directly relevant to crop

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