coal liquefaction can be improved, and costs lowered significantly through a steady research effort.

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Cooling, Stopping, and Trapping Atoms

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Significant advances have been made in the ability to control the motion of neutral atoms. Cooling and trapping atoms present new possibilities for studies of ultracold atoms and atomic interactions. The techniques of laser cooling and deceleration of atomic beams, magnetic and laser trapping of neutral atoms, and a number of recent advances in the use of radiative forces to manipulate atoms are reviewed.

THIS ARTICLE REVIEWS THE USE OF ELECTROMAGNETIC forces, particularly radiative forces, to influence atomic motion. Earlier reviews (*1*) have given good accounts of both experimental and theoretical work in this field. We concentrate on advances in the manipulation of neutral atoms, especially laser cooling of atomic beams and electromagnetic trapping of atoms.

Thermal motion of atoms is the bane of many measurements in atomic physics. The precision of ultrahigh-resolution atomic spectroscopy is invariably limited by the motion of the atoms being observed. Doppler effects both shift and spread the frequencies associated with transitions between atomic energy levels. A host of techniques that are based on the use of nonlinear laser spectroscopy, as well as spectroscopy with laser beams perpendicular to a well-collimated atomic beam, have provided the means of observing optical spectra that are nearly free of the first-order Doppler effect. Unfortunately, the second-order Doppler effect, associated with the relativistic time dilation, is unaffected and continues to plague the spectroscopist. The finite observation times available when one looks at rapidly moving atoms also limit the precision with which measurements can be made. As a result, the best spectroscopic measurements, from radio to optical frequencies, are limited by motional effects (*2, 3*).

Detailed studies of collision phenomena, which require precise knowledge of the initial velocities of the collision partners, are similarly hampered by the randomness of thermal motion. Neither the direction nor the magnitude of the relative velocity of two colliding atoms is well defined when velocities are distributed thermally. The use of thermal atomic beams, for which the direction of each atom's velocity is well defined, does not completely solve the problem. Velocity selection of an atomic beam leads to a well-defined velocity, but selection is inefficient in that most of the atoms are not used. Velocity compression by means of supersonic expansions can yield high beam flux with relatively well-defined velocity,

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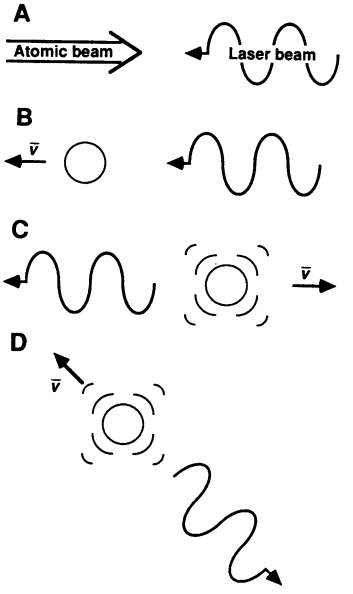

Fig. 1. Sketch of the laser cooling process. (**A**) Laser cooling of an atomic beam with a counter-propagating laser beam. (**B**) The velocity change of an atom caused by the absorption of a photon from the laser. (**C**) The velocity change that results from stimulated emission of a photon. (**D**) The random recoil caused by spontaneous emission.

but low velocities are not attainable in this manner. A laser-cooled atomic beam, on the other hand, makes efficient use of the atoms, and achieves a narrow and selectable velocity. It has the additional advantage of being able to place all the atoms in a single internal quantum state and at quite low velocities.

Some interesting collision processes become important only at low velocities. When the velocity of the collision partners is low enough, the corresponding de Broglie wavelength becomes long compared to the range of their interaction potential. Under these conditions the collision partners cannot be treated as if they had a classical trajectory, and the collision is dominated by quantum effects. Furthermore, at sufficiently low energy, the molecular spectroscopy of free-bound transitions can become as well resolved as that of bound-bound spectroscopy, since the energy width of the continuum (free) state can become as small as the width of the (excited) bound state (*4*).

In addition, many other kinds of experiments with atomic beams, such as studies of the deflection of atoms by light (*5*), tests of photon statistics (*6*), searches for intrinsic electric dipole moments (*7*), and tests of charge neutrality (*8*), would benefit from reduction of the thermal motion of the atoms. Finally, some interesting effects, such as Bose condensation, only occur when atoms are traveling so slowly that their quantum nature becomes predominant.

To overcome these problems of thermal motion, atomic physicists have pursued two goals, (i) the reduction of the thermal motion (cooling) and (ii) the confinement of the atoms by means of electromagnetic fields (trapping). Cooling, carried sufficiently far, eliminates the motional problems, whereas trapping allows for long observation times. The obvious way to cool atoms is to put them in a refrigerated container and let them give up their thermal energy to its walls. Unfortunately, at a low enough temperature virtually any atom will condense onto the walls. An electromagnetic trap, which is just a container without material walls, is an answer to this dilemma. But then the question becomes, how does one cool the atoms (extract energy from them) if they never touch anything?

Laser Cooling

One answer to this question was given in 1975 by two independent proposals (*9*) for cooling atoms, not by collisions with cold walls, but by collisions with "cold" laser photons. When an atom absorbs the energy of a photon, making a transition to a more highly excited energy state, it also absorbs the momentum of the photon. This changes the atomic velocity. Laser cooling is the use of this velocity change to reduce the thermal motion.

To see how this works, consider a laser irradiating a gas of atoms, with the laser frequency tuned below the frequency for resonant absorption. Atoms moving toward the laser slow down as they absorb photons since the photon momentum opposes their motion. Atoms moving away from the laser speed up.

The key to laser cooling is that the atoms moving toward the laser absorb photons at a higher rate than those moving away because they see the laser frequency Doppler-shifted closer to resonance. Thus, on the average, atoms have their kinetic energy reduced by interacting with the laser. This condition would be reversed (that is, the atoms would be heated) if the laser frequency were tuned above the atomic resonance. For a single, unidirectional laser beam, all the atoms would be accelerated in the direction of the beam, and the average velocity would grow, even though the velocity spread would be decreasing. This acceleration can be avoided by using counter-propagating laser beams or by placing the atoms in a trap.

Laser cooling was first demonstrated on trapped ions (*10*). Cooling of ions has led to the development of important areas of research such as improved spectroscopy and frequency standards (*11*); millikelvin ionic temperatures (*12, 13*); tests of spatial anisotropy (*14*); confinement of atoms to less than an optical wavelength (the Lamb-Dicke regime) (*13, 15*); Doppler-free, recoilless spectroscopy (*13, 15*); and observation of quantum jumps on single ions (*16*). The laser cooling of ions is greatly facilitated because their charge permits the ions to be trapped in deep wells. This allows long interaction times and the transfer of many photon momenta.

The extension of laser cooling to neutral atoms was not easy. A basic problem was that no neutral atom traps could contain atoms with typical thermal energies. While ions could first be trapped and then laser-cooled, neutrals had to be laser cooled before they could be trapped.

Laser cooling of free atoms is accomplished by directing a laser beam against an atomic beam (see Fig. 1). The atoms of mass M absorb photons of frequency ν having momentum $h\nu/c$ (where c is the velocity of light and h is Planck's constant), which reduces their velocity v by $h\nu/Mc$ for each absorption. The atom also receives a velocity kick when it radiates a photon by spontaneous or stimulated emission. For excitation by a plane-wave laser beam, stimulated photons go off in the same direction as the incoming photons. So, they cancel the momentum transferred by the absorbed photon. The spontaneous photons, however, go off in random directions. The momentum transfer is zero on average, and so the net momentum transfer after absorption followed by spontaneous emission is the momentum transfer of the absorption. Because the transfer of a net momentum depends on spontaneous emission, the radiation pressure force produced is often called the spontaneous force. For sodium atoms (used in most experiments) the initial thermal atomic velocity is about 1000 m sec^{-1}, and the velocity change per photon absorbed is 3 cm sec^{-1}. This means that a sodium atom must absorb and emit over 3×10^4 photons to be stopped.

Since the deceleration requires spontaneous emission, it is limited by the rate of spontaneous emission. The maximum rate of velocity change is $h\nu/2Mc\tau$, where τ is the natural lifetime for spontaneous emission of a photon from the excited state. For sodium, this corresponds to an acceleration of about 10^6 m sec^{-2}, 10^5 times the gravitational acceleration g. This would be sufficient to bring thermal sodium atoms to rest in 1 msec over a distance of 0.5 m, quite a reasonable laboratory scale. Unfortunately, two phenomena conspire to prevent the achievement of this maximum deceleration, optical pumping and the Doppler shift.

Optical Pumping

Figure 2A, which shows part of the energy-level structure of sodium, illustrates the problem of optical pumping. The levels are characterized by F (ground state) or F' (excited state), the total atomic angular momentum. When an atom that is initially in the ground $3S_{1/2}$ ($F = 2$) level is excited by the cooling laser to the $3P_{3/2}$ ($F' = 2$) level, it may spontaneously decay to the $3S_{1/2}$ ($F = 1$) level. The energy of this level lies sufficiently far (1772 MHz) below the $F = 2$ level that there is little likelihood of the atom being excited by the same laser that excited it from the original ($F = 2$) level. Eventually all the atoms are optically "pumped" into this inaccessible level. The selection rule that requires $\Delta F = F' - F$ to be ± 1 or 0 in any optical transition results in the $F = 2 \leftrightarrow F' = 3$ transition being a closed cycle. Even with the laser tuned to this "cycling" transition, however, there will be some leakage into the $F = 1$ state. Because of the close proximity (60 MHz) of the $F' = 2$ level to the $F' = 3$ level, some excitation of $F' = 2$ (and subsequent decay to $F = 1$) is unavoidable. This allows only a few hundred of the required 3×10^4 photons to be scattered before optical pumping ends the cooling process.

One solution to the problem is to use another laser frequency to excite or "repump" atoms out of the ground $F = 1$ level. This two-frequency technique has been used successfully by a number of groups cooling neutral atoms (*17–19*) and has also been used in cooling ions (*20*).

We have taken a different approach to the optical pumping problem. Rather than correct the problem with another laser frequency, we prevent it by the use of additional selection rules (*21*). Figure 2B shows the sodium energy levels in a magnetic field. The various F levels split according to their projection m_F of the total angular momentum onto the magnetic field direction. We impose the magnetic field, and thus define the quantization axis, along the axis of the atomic and laser beams. The laser light is circularly polarized and carries angular momentum. The direction of polarization is chosen so that the atoms absorbing the light must increase the projection of their angular momentum ($\Delta m_F = +1$). For atoms in the $F = 2$, $m_F = 2$ ground state, the only state to which they can be excited is $F' = 3$, $m_F' = 3$.

The selection rule for decay ($\Delta m_F = \pm 1,0$) guarantees return to the $F = 2$, $m_F = 2$ state. In a high enough magnetic field (about 500 G for sodium) the projection of the nuclear angular momentum m_I becomes a good quantum number in the excited state, and the selection rule $\Delta m_I = 0$ suppresses unwanted transitions (to states other than $F' = 3$, $m_F' = 3$) that might occur because of imperfect polarization or alignment of the field. Other, partly allowed, transitions are suppressed because the field shifts them far out of resonance. All these suppressions allow an atom to make many transitions without being pumped to an inaccessible state. A bonus of this technique is that the light transfers angular momentum to the atoms. Thus, because of off-resonant transitions, all the atoms, regardless of their initial state, eventually end up in the states with highest projection of angular momentum, cycling on the $F = 2$, $m_F = 2 \rightarrow F' = 3$, $m_F' = 3$ transition.

Circular polarization, without a magnetic field, can also be used with the two-frequency technique to reduce the power needed in the repumping laser. Under these conditions, most atoms cycle on the (2,2) → (3,3) transition, but only with a strong magnetic field is the leakage to other states so small that a second laser frequency is not needed.

Compensation of Doppler Shifts

Once the problem of optical pumping is solved, either by multiple laser frequencies or by selection rules, we are faced with the second problem, the Doppler shift. After a sodium atom absorbs a few hundred photons, its velocity changes enough so that the laser frequency is Doppler-shifted out of resonance. Scattering of just 100 photons will change the atomic velocity by 3 m sec^{-1}, giving a Doppler shift of 5 MHz, enough to change the photon absorption rate by a factor of 2. The result is that only a small number of atoms (those with the correct initial velocity to be near resonance with the laser) are decelerated by only a small amount (the few meters per second needed to take them out of resonance with the laser). In spite of this, the effect on the velocity distribution in an atomic beam can be quite dramatic, as is seen in Fig. 3. The production of a very narrow feature in the velocity distribution comes about as those atoms that were initially nearly resonant with the laser are pushed to lower velocities where they "pile up" as they go out of resonance and no longer experience significant changes in their velocities. This type of cooling, which we call "pushing" or nonresonant cooling, has been theoretically studied (*22*) and constituted the first clear experimental demonstration of laser cooling of an atomic beam, by

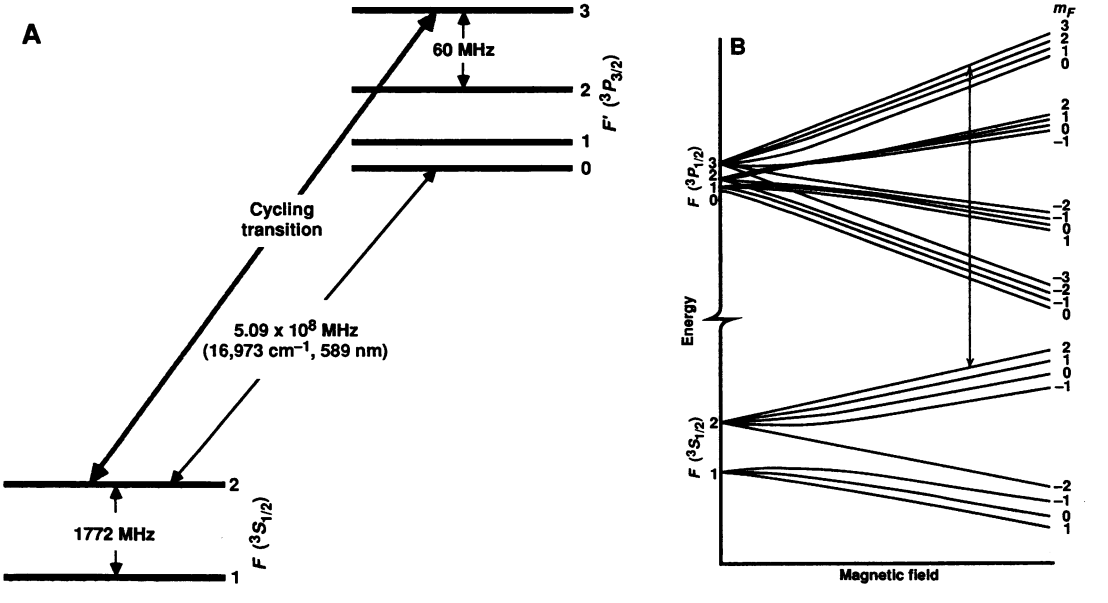

Fig. 2. (**A**) Sodium energy-level diagram (not to scale). The atoms are cooled by repeated excitation and spontaneous emission on the "cycling transition." (**B**) Sodium energy levels in a magnetic field (not to scale). Cycling transition is shown.

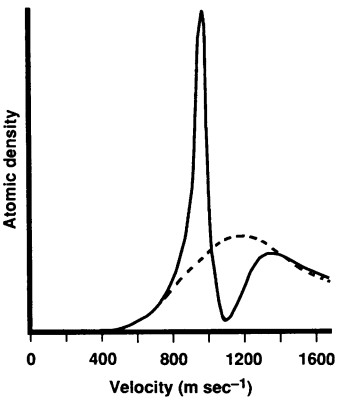

Fig. 3. Deceleration and cooling with the nonresonant, "pushing" technique. The dotted curve indicates the atomic velocity distribution before cooling, and the solid curve shows the effects of cooling.

the group at the Institute of Spectroscopy in Moscow (*23*).

To cool a large fraction of the atoms in an atomic beam by a significant amount, it is necessary to compensate for the change in Doppler shift that takes the atoms out of resonance with the cooling laser. Although many methods have been suggested for doing this, only two have actually been used. In the first of these (*24*) the frequency of the laser is changed as the atoms decelerate so as to keep the laser in resonance with the atoms. This technique of cooling with a rapid frequency change ("chirp cooling") was first attempted in experiments by Balykin *et al.* (*25*) at the Institute of Spectroscopy in Moscow in 1979. We first used the technique to produce significant deceleration and compression of an atomic velocity distribution in 1983 (*26*). It was used to stop atoms at the National Bureau of Standards (NBS) in Boulder (*17*), and since then a number of groups have adopted the technique. With the exception of the early Soviet experiments and our own, all of these groups have used the two-frequency method to avoid optical pumping in chirp cooling.

The second method for compensating for the changing Doppler shift, which was developed in our laboratory (*21*), is the use of a spatially varying magnetic field to Zeeman shift the atomic resonance frequency so as to keep the atoms in resonance with a fixed-frequency cooling laser. This "Zeeman cooling" differs from chirp cooling in that it is a continuous process, whereas chirp cooling produces pulses of cooled atoms at the end of each laser frequency scan. The effect of Zeeman cooling on an atomic velocity distribution is shown in Fig. 4. The effect of chirp cooling is very similar.

Zeeman cooling has the disadvantage of needing a magnetic field, but it is particularly well suited to the prevention of optical pumping problems through the use of selection rules and it has the advantage of producing all of the cooled atoms in the same quantum state. This can be particularly advantageous for trapping or collision experiments. In addition, Zeeman cooling produces a spatial compression of atoms because all atoms are brought to rest (or to some final velocity) at the same location in the solenoid.

Both Zeeman and chirp cooling can produce large reductions in the atomic velocity as well as compression of the velocity spread. (Strictly speaking, only the velocity compression should be called "cooling," but we often use the term to include deceleration as well.) These techniques have produced samples of atoms with near zero average velocities and longitudinal velocity spreads that are characteristic of temperatures in the millikelvin range (*17, 27*).

In order to further cool the nearly stopped atoms, one needs a different technique. The unidirectional laser beam used to decelerate and cool an atomic beam is inappropriate for cooling a free gas that has no mean velocity. For this we need to irradiate the atoms with symmetric or balanced counterpropagating laser beams, tuned below resonance. In this arrangement atoms are always slowed, regardless of the direction of their velocity. The method is typically used when the spread in atomic Doppler shifts is comparable to or smaller than the natural line width, so no Doppler compensation is needed. The atoms cool to an equilibrium temperature determined by the balance between cooling and heating from spontaneous emission. The lowest achievable temperature or "cooling limit" is on the order of the energy width of the excited atomic state.

Experiments at the Institute of Spectroscopy in Moscow have used such symmetric cooling in two dimensions to reduce the transverse temperature of an atomic beam (*28*). Researchers at AT&T Bell Laboratories have used three-dimensional cooling to reduce the energy approximately to the cooling limit (below 1 mK) (*18*). The optical damping of atomic motion achieved in this way is so strong that the atoms execute diffusive motion under its influence, as if in viscous fluid. Hence, this strong cooling is known as optical "molasses" and has the additional benefit of retaining the atoms in the cooling region for times much longer than the ballistic transit time (*18, 29, 30*).

In recent experiments at NBS in Gaithersburg, Maryland, we have continuously loaded optical molasses with atoms from a laser-cooled atomic beam. Figure 5 shows the experimental configuration used to make and load the molasses. We have observed steady-state densities of 10^8 cm^{-3} and decay times of over 0.5 second in a molasses region about 1 cm in diameter (*30*). In the absence of the molasses effect, the atoms would leave the region in about 10 msec.

The production of samples of atoms with millikelvin and submillikelvin temperatures has made it possible for the atoms to be electromagnetically trapped. It has long been possible to trap ions by means of electric and magnetic fields. The forces exerted on ions by such fields are so strong that room-temperature (25 meV) ions are easily trapped, and recently antiprotons with energies of 3 keV have been trapped (*31*). Forces that can be exerted on neutral atoms are, by comparison, quite small. Only by laser cooling have atoms been brought to low enough energies that such small forces can trap them.

Magnetic Atom Traps

The first published proposal for trapping neutral atoms (*32*) is now nearly 30 years old. The proposed trapping force is provided by the action of a nonuniform magnetic field on an atom having a permanent magnetic dipole moment. Such forces had already been used in the famous Stern-Gerlach experiment to deflect atoms (*33*) and by Friedburg and Paul to focus them (*34*). But the trapping energy associated with such forces is just the magnetic moment multiplied by the maximum field change. For an atom with a magnetic moment of 1 Bohr magneton and a trap with 2-T field change, the trap depth, or maximum energy that can be confined in

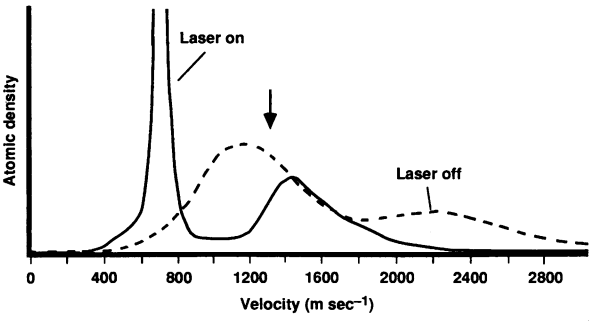

Fig. 4. Results of Zeeman-tuned cooling. Dotted and solid curves are as in Fig. 3. The arrow indicates the highest velocity resonant with the cooling laser. The velocity scale refers only to atoms in the $F = 2$ state.

the trap, is only about 1 K. Ultracold neutrons were confined in a magnetic trap (a storage ring) in 1978 (*35*), but trapping of neutral atoms had to wait for the development of laser cooling to produce sufficiently slow atoms.

Experiments in our laboratory in 1985 combined the techniques described above for slowing and stopping an atomic beam with an extension of the technique, called "postcooling" (*27*). This provided atoms with sufficiently low energy to demonstrate the first neutral atom trap (*36*). In this experiment, atoms are continuously brought to rest in the tapered solenoid near the exit end (see Fig. 6). When the cooling laser is shut off, atoms that have not reached the end of the solenoid, and have therefore not yet been stopped, are allowed to leave the solenoid and travel unimpeded to the trap region. Here, the cooling laser is again turned on, for just long enough to bring the average velocity of the atoms to zero. Then, the magnetic field of the trap is switched on, confining the slow atoms and holding them in the magnetic bottle.

The trap itself consists of two coaxial coils with oppositely directed currents. This configuration produces zero field at the center of the pair of coils and a field magnitude that increases linearly with any displacement from the center. For atoms with magnetic moments oriented such that their potential energy increases with increasing field magnitude (as is the case for our laser-cooled atoms), this constitutes a potential energy well with a minimum at the center. The trap holds atoms for average times of about 1 second, a trapping time limited by collisions with background gases in our imperfect vacuum (*36*). Since the background atoms are at room temperature, a collision generally transfers more than enough energy to eject a cold atom from the trap.

The trap has a volume of 20 cm^3, a depth of 17 mK, and in the first experiments held a few tens of thousands of atoms. More recently, magnetic traps with stronger fields, bigger volumes, and better vacuums have held atoms for times longer than 1 minute (*37*).

Laser Traps

The next trap to be demonstrated was a laser dipole trap. Whereas the magnetic trap relies on the force of an inhomogeneous, static magnetic field acting on the permanent magnetic moment of an atom, the laser trap relies on the force of an inhomogeneous, oscillating electric field of a laser acting on an induced, oscillating electric dipole moment of an atom. This force is called the induced, gradient, or dipole force, and has undergone considerable theoretical study (*38*). In strong laser fields the dipole force can be substantially larger than the ordinary radiation pressure force used for cooling and stopping atoms. The phase of the driving field with respect to the induced moment is such that when the laser is tuned below the resonance frequency of the atom, the atom is drawn into the strongest part of the laser field.

Confinement of atoms by means of the dipole force was first proposed by Letokhov nearly 20 years ago (*39*). As in the case of magnetic traps, the well depth of a laser dipole trap is quite small, so its realization had to await successful laser cooling. An additional complication is that the laser trap heats the atoms, so continuous cooling is required to keep the atoms from "boiling" out of the trap. Recently, a group at AT&T Bell Laboratories combined an elegant trap design proposed by Ashkin (*40*) and a cooling scheme devised by Dalibard *et al.* (*41*) with their own recently demonstrated optical molasses (*18*) to produce the first laser trap (*42*). With a well depth of only 5 mK it held a few hundred atoms in a volume of 10^{-9} cm^3 for an average of about a second, limited, as in the case of our magnetic trap, by the imperfect vacuum.

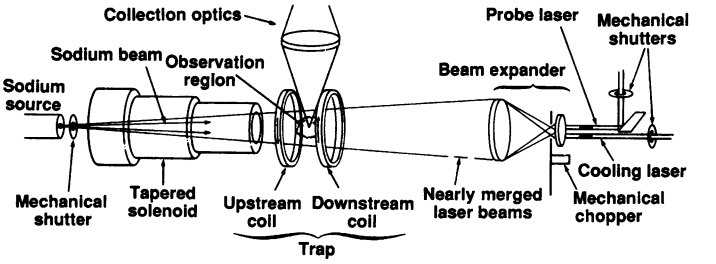

Fig. 6. Schematic of the apparatus used for the magnetic trapping of neutral atoms. The solenoid is 1.1 m long, and the trap is 40 cm from the end of the solenoid.

The dipole trap consists of a single, strongly focused laser beam with a Gaussian intensity profile, providing a field with an absolute maximum of laser intensity at the center of the focus. This focus is imbedded in optical molasses. Slow atoms from the molasses fall into the trap and are concentrated from a density of 10^6 cm^{-3} in the molasses to nearly 10^{12} cm^{-3} at the center of the trap. The trapping laser is tuned several hundred gigahertz below resonance to minimize the "spontaneous" radiation pressure force, which would otherwise push the atoms out of the trap. The molasses beams provide the cooling needed to stabilize the trap against its own heating mechanisms. This cooling would be rendered ineffective because of the large energy-level shifts induced by the strong trap fields, so the trap is shut off periodically, allowing the cooling to work, then switched back on before the atoms can escape.

Although laser dipole traps were the first optical traps to be suggested and to be demonstrated, there has also been considerable interest in another kind of radiative trap, one that depends on the spontaneous radiation pressure or scattering force. In a dipole trap, the large forces are achieved by tight focusing of the laser beam, which gives a large intensity gradient but results in small volumes. The power densities used are typically many times as great as the saturation intensity, a condition that exacerbates problems with heating and cooling. By contrast, radiation pressure traps require power densities only on the order of saturation, which permits the trap to be bigger and deeper for a given amount of laser power. The modest intensity makes heating less of a problem and can even allow the trapping beams to provide cooling as well. As early as 1970 Ashkin (*43*) proposed using spontaneous radiation pressure to dynamically confine atoms moving in a ring; in 1978 he proposed a hybrid trap that combined dipole and radiation pressure forces (*40*).

It was proposed that static, pure radiation pressure traps with a single equilibrium point could be configured (*44*), but Ashkin and Gordon showed that, just as it is impossible to stably trap a charged particle with static electric fields in a charge-free region of space (Earnshaw's theorem), such traps are impossible for static radiation fields that exert forces proportional to their intensity (*45*). Ashkin (*46*) and Dalibard and Phillips (*47*) discussed ways in which this "optical Earnshaw theorem" could be circumvented by switching the laser fields on and off, violating the condition on the static nature of the light field. Later, Pritchard *et al.* (*48*) showed that the

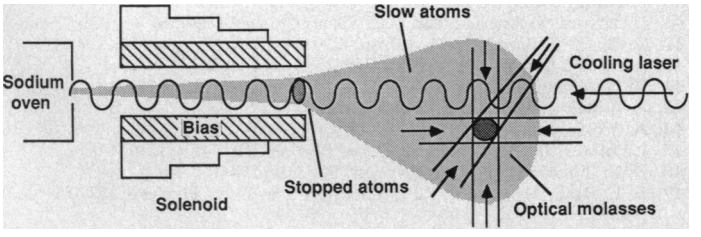

Fig. 5. Schematic of the experimental apparatus used for studies of optical molasses.

condition concerning proportionality of force and intensity could be violated so as to make a trap. A collaboration of groups at the Massachusetts Institute of Technology (MIT) and AT&T Bell Laboratories has recently made such a trap, confining sodium atoms at densities higher than 10^{11} cm^{-3} in a volume of about 10^{-4} cm^3 for times longer than a minute (*49*).

We should point out that all of the traps for neutral atoms described here strongly perturb the energy levels of the atoms. Zeeman shifts, light shifts, or combinations of these change the energy levels of the atom in a spatially dependent way. These shifts complicate the prospect of high-resolution spectroscopy in traps. Although some trap designs might minimize the effects of perturbations, it may be necessary to conduct the spectroscopy of cold neutral atoms in the absence of trapping.

Other Developments

There have been a host of recent developments in cooling, trapping, and the use of radiative forces to influence the motion of atoms. The group in Moscow has collimated, focused, and imaged an atomic beam by means of radiation pressure (*50*). They have also realized a proposal of Cook and Hill (*51*) to reflect atoms from an atomic mirror with the dipole force exerted by an evanescent wave (*52*). These experiments on the refraction and reflection of matter by light offer an interesting complement to the usual refraction and reflection of light by matter.

The MIT group has demonstrated diffraction of an atomic beam by a standing wave of light (*5*), the complementary process to the usual diffraction of light by a material grating. A group at Ecole Normale Supérieure in Paris has used dipole forces to transversely cool an atomic beam (*53*) and to confine atoms in one dimension within the nodal planes of a standing light wave (*54*). A group in Aarhus, Denmark, has demonstrated the first laser velocity modification of a fast (100 keV) metastable atomic neon beam (*55*), while a group in Tokyo has performed laser cooling and stopping of a thermal metastable neon beam (*56*). Proposals have been put forth for cooling atoms below the usual limit for laser cooling (*57*). At MIT, hydrogen atoms have been held in a magnetic trap, a new advance in the search for Bose condensation in spin-polarized hydrogen (*58*). At the University of Colorado in Boulder, diode lasers have been used to make optical molasses and a novel optical trap for cesium (*59*). In our laboratory at NBS we have recently demonstrated a hybrid radiation pressure–dipole force optical trap on the basis of the two-focus design proposed by Ashkin (*40*). This trap has been used to make the first submillikelvin measurements of a collision cross section. New measurements on optical molasses in our laboratory have shown that the simple theory of viscous damping is insufficient to explain the molasses behavior, and observations of a curiously long-lived "super molasses" at AT&T Bell Laboratories and in our laboratory reinforce the conclusion that there is still much to be understood about radiative forces on atoms (*30*).

The development of the field of laser cooling, trapping, and manipulation of atoms has been truly remarkable. As recently as 1983, no trapping of atoms had been demonstrated, the possibility of stable optical traps was seriously in doubt, and laser cooling of atomic beams was the exclusive domain of one or two laboratories. Now, both magnetic and laser traps of various kinds have been demonstrated and laser cooling of atomic beams is practiced in at least a dozen laboratories around the world. The range of possible applications now goes well beyond the original interest in high-resolution spectroscopy and includes serious programs for atom-atom and atom-surface collision studies at ultralow energy and for cooling and trapping applications to Bose condensation. The future of laser cooling and trapping looks exceedingly bright.

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Cortical Flow in Animal Cells

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A concerted flow of actin filaments associated with the inner face of the plasma membrane may provide the basis for many animal cell movements. The flow is driven by gradients of tension in the cell cortex, which pull cortical components from regions of relaxation to regions of contraction. In some cases cortical components return through the cytoplasm to establish a continuous cycle. This cortically located motor may drive cell locomotion, growth cone migration, the capping of antigens on a lymphocyte surface, and cytokinesis.

OUR PURPOSE IN WRITING THIS ARTICLE IS TO SUGGEST how many surface movements of animal cells may be integrated. Observations of the migration of fibroblasts, amoebae, and white blood cells over surfaces; the growth of axons; the capping of antibodies on a lymphocyte; and the changes in shape as cells divide all point to the existence of a concerted flow of actin-containing structures within a cortical region subjacent to the plasma membrane. The movements originate at a specific region of the cell surface—the leading edge of a migrating cell, for example, or the polar region of a dividing cell—and carry material back over the cell surface to a more proximal position. (Why these movements arise at a particular region of the cell surface will not concern us here but may depend on the disposition of cytoskeletal elements such as microtubules in the cytoplasm.) In most cases, it seems necessary to postulate a compensatory forward flow of actin-containing components within the cytoplasm giving rise to a "fountain flow" of cortical components within the cell. These cortical movements are probably a consequence of the contractile nature of the cell cortex and have a number of important implications for the behavior of animal cells, especially in response to contact with solid substrata.

The idea of a concerted flow of surface structures is not new. Suggestions of a similar nature date back to the latter part of the 19th century, when light microscopic observations of freshwater amoebae of the *Amoeba proteus* type revealed the active streaming of cytoplasm that accompanies pseudopodial extension. These observations gave rise to a model for the locomotion of giant amoebae in which the flow of centrally located, more fluid cytoplasm into a pseudopodium is driven by a contraction of cortical cytoplasm at the tail of the cell. With the development of tissue culture methods in the present century, it became possible to examine the locomotion of the much smaller cells from vertebrate tissues, and the suggestion arose that they too possess a "superficial plasmagel," although no layer could be discerned directly by light microscopy. Lewis was one of the earliest protagonists of this view, and in a prescient article published in 1939, he postulated that regional contractions in a cortical layer in white blood cells could provide a driving force for both cell locomotion and cell division (*1*). A similar suggestion is a central tenet of this article.

Despite their venerable origins, global aspects of cell behavior are often overlooked with the contemporary emphasis on detailed molecular mechanisms. We believe that it is useful to reexamine the question of cortical flow in light of information acquired in the intervening years. Many detailed observations of cell movements not considered by Lewis and his contemporaries, such as the migration of fibroblastic cells over planar surfaces, are now available. Certain molecular mechanisms that may power their large-scale movements can now be identified.

The Actin-Rich Cortex of Animal Cells

Lewis's "superficial plasmagel layer" is now known to consist of a complex network of actin filaments and associated proteins attached to the inner face of the plasma membrane (*2*). This cortical layer has both elastic and viscous properties and maintains an isotropic tension that resists deformation, providing a resilient framework for the otherwise flimsy lipid bilayer (*3*). The cell cortex has the capacity to undergo local contractions, which are seen most clearly in the waves of contraction that travel over the surfaces of many eggs (*4*). More generally, local contractions together with changes in the structure and composition of the cortical layer and the generation of actin-containing extensions on the cell surface form the basis of cell locomotion, cell division, phagocytosis, and the changes in cell shape that accompany tissue morphogenesis.

A central challenge of contemporary cell biology is to explain cell movements and shape determination in terms of the molecules involved. Toward this end, several dozen proteins able to bind to actin and modify its properties have been identified; the majority of these proteins are present in the cell cortex (*5*). Some actin-binding proteins affect the ability of actin monomers to polymerize into

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