NEW MECHANISMS FOR LASER COOLING

Optical pumping and light shifts have unexpectedly conspired to improve laser cooling by orders of magnitude and to produce the lowest kinetic temperatures ever measured.

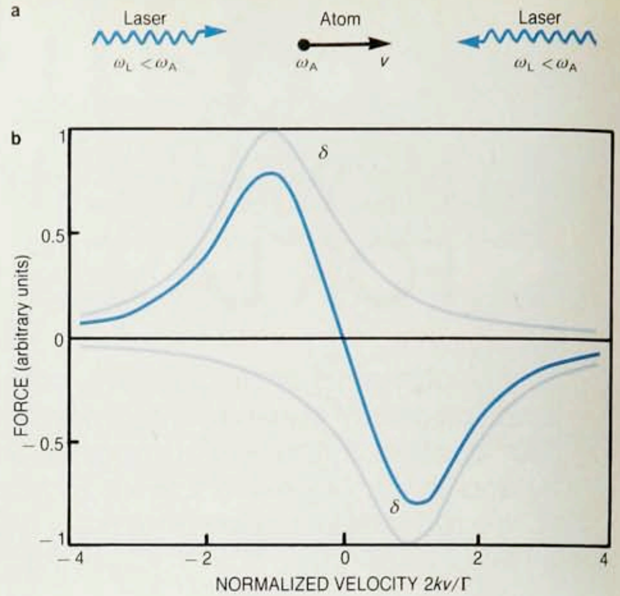
Claude N. Cohen-Tannoudji and William D. Phillips

When an atom or a molecule interacts with a light beam, the light emitted or absorbed carries valuable information about the atomic or molecular structure. This phenomenon underlies the whole field of spectroscopy. But the interaction of a photon with an atom can be used to manipulate the atom as well as to probe its structure. For example, in an approach called optical pumping, invented by Alfred Kastler, one can use the resonant exchange of angular momentum between atoms and polarized photons to align or orient the spins of atoms or to put them in nonequilibrium situations. In his original 1950 paper Kastler also proposed using optical pumping to cool and to heat the internal degrees of freedom, calling the phenomena the "effet luminofrigorique" and the "effet luminocalorique." Another famous example of the use of photon–atom interaction to control atoms is laser cooling. This technique relies on resonant exchange of linear momentum between photons and atoms to control their external degrees of freedom and thus to reduce their kinetic energy. Laser cooling was suggested independently by Theodor Hänsch and Arthur Schawlow for neutral atoms[1] and by David Wineland and Hans Dehmelt for trapped ions.[2] In an article written three years ago for PHYSICS TODAY (June 1987, page 34), Wineland and Wayne Itano presented the principle of laser cooling and the potential applications of cold atoms to fields of physics such as ultrahigh resolution spectroscopy, atomic clocks, collisions, surface physics and collective quantum effects. At that time laser cooling had brought temperatures down to a few hundred microkelvin, but unexpected improvements during the last three years have dramatically lowered those temperatures to only a few microkelvin. We now feel we understand the new physical mechanisms responsible for these very low temperatures.

Doppler cooling: The traditional mechanism

The principle of Doppler cooling for free atoms[1] can best be illustrated by a two-level atom in a weak laser standing wave with a frequency ω_L slightly detuned below the atomic resonance frequency ω_A (see figure 1a). Each of the two counterpropagating laser beams forming the standing wave imparts an average pressure in its direction of propagation as the atom absorbs photons in that direction but radiates the photons isotropically. Suppose first that the atom is at rest. The radiation pressures exerted by the two counterpropagating waves exactly balance, and the total force experienced by the atom, averaged over a wavelength, vanishes. If the atom is moving along the standing wave at velocity v, the counterpropagating waves undergo opposite Doppler shifts $\pm\omega_L v/c = \pm kv$, where k is the magnitude of the wavevector. The frequency of the wave traveling opposite to the atom gets closer to resonance and this wave exerts a stronger radiation pressure on the atom than the wave traveling in the same direction as the atom, which gets farther from resonance. This imbalance between the two

Claude Cohen-Tannoudji is a professor at the Collège de France and does research at the Ecole Normale Supérieure in a laboratory associated with the University of Paris VI and with Centre National de la Recherche Scientifique.
William Phillips is a physicist at the National Institute of Standards and Technology (formerly the National Bureau of Standards) in Gaithersburg, Maryland.



Principle of Doppler cooling. (**a**) An atom moves along the standing wave set up by two counterpropagating laser beams, each with a frequency below the atom's resonance frequency by a small amount δ. (**b**) At low intensities the atom feels average forces in opposite directions from the two beams (light blue curves), with the peaks offset because of the laser detuning. The net force (dark blue curve) is the friction that cools the atom. The slope at $v = 0$ is the friction coefficient. For the curve shown δ is exactly half the natural linewidth of the excited state. **Figure 1**

radiation pressures gives rise to an average net friction force F, which is opposite to the atomic velocity v and which can be written, if v is low enough, as $F = -\alpha v$, where α is a friction coefficient.

Figure 1b shows, for low laser intensity I_L, the damping (cooling) force as the sum of two opposing forces that vary with kv as Lorentzian curves, each curve having a width Γ equal to the natural width of the excited state. These curves are centered at $kv = \pm\delta$, where $\delta = \omega_L - \omega_A$ is the amount by which the frequency is detuned from resonance. The slope of the total force at $v = 0$, that is, the friction coefficient α, is maximum when $\delta \simeq -\Gamma/2$. The total force is then proportional to the laser intensity, always opposes the velocity and is nearly linear in velocity for $|kv| < \Gamma/2$. This inequality defines a range v_D of velocities (called the velocity capture range) over which the atomic motion is most effectively damped by Doppler cooling. For low I_L this range is independent of I_L.

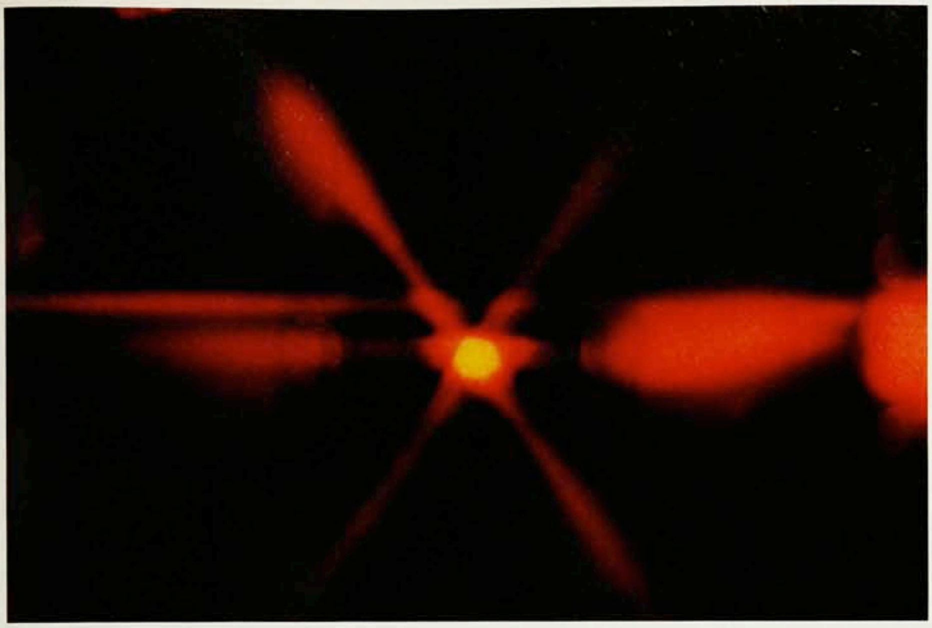
Actually, the friction force considered above is only a mean force, averaged over several fluorescence cycles. The random nature of radiative processes introduces fluctuations in atomic motion. For example, each individual fluorescence photon is emitted in a random direction, giving a random recoil to the atom. Furthermore, the number of fluorescence cycles occurring during a given time interval is random, so that the momentum absorbed from the laser beams by the atom during this time interval is also random. As in Brownian motion, these fluctuations in momentum exchanges tend to increase the width Δp of the atomic momentum distribution. The corresponding heating rate is characterized by the rate of increase of $(\Delta p)^2$, that is, by the momentum diffusion coefficient D, which can be shown to be proportional to the laser intensity I_L. In the steady state the heating rate, characterized by D, is balanced by the cooling rate, characterized by the friction coefficient α, and the atom reaches an equilibrium temperature T that is proportional to D/α. Since both D and α are proportional to the laser intensity I_L, T is predicted to be independent of I_L (in the limit of low I_L). From the theoretical expressions for D and α, one can show[3] that the lowest temperature T_D that can be achieved by Doppler cooling is given by $k_B T_D = \hbar\Gamma/2$. This "Doppler limit" is obtained for a frequency detuning of $\delta = -\Gamma/2$. For sodium, T_D is approximately 240 μK, whereas for cesium it is about 125 μK.

Other two-level cooling mechanisms using stimulated emission processes in an intense laser standing wave have been proposed[4] and demonstrated,[5] but they will not be considered here. They give rise to larger friction coefficients but higher equilibrium temperatures.

Three-dimensional cooling of untrapped atoms requires multiple laser beams. Hänsch and Schawlow[1] suggested a configuration of six beams arranged as three orthogonal pairs. With the beams configured in this way the strong damping provided by Doppler cooling can produce not only low temperatures, but also viscous confinement. Sodium atoms subject to the friction force described above would have such a short mean free path that they would take longer than 1 second to diffuse a centimeter. By contrast, if they moved ballistically at their cooling limit velocity, they would move a centimeter in 20 msec. This confinement is similar to that of a particle in Brownian motion in a viscous fluid. The confinement capability of laser cooling was first realized and demonstrated at Bell Laboratories in 1985 by Steven Chu (now at Stanford University) and his colleagues.[6] They gave the name "optical molasses" to this laser configuration. Figure 2 shows sodium atoms viscously confined in an optical molasses.

The Bell Labs group measured the temperature of the sodium atoms in the "molasses" by studying their ballistic motion after the confining laser beams were shut off. The rate at which the released atoms left the confinement volume allowed the group to determine the temperature. The interpretation of the data depends on the dimensions of the confinement volume and the distribution of atoms within that volume at the time of release. The result of 240^{+200}_{-60} μK included the expected Doppler cooling limit. Furthermore, the diffusion time of the atoms out of the molasses agreed fairly well with the expected value, so optical molasses and the laser cooling process appeared to be well understood.

Subsequent experiments at the National Institute of Standards and Technology[7] and at Bell Labs[8] soon cast



Sodium atoms in optical molasses. The molasses, or region in which the laser pressure cools and viscously confines atoms, is the bright region at the intersection of three orthogonal pairs of counterpropagating laser beams. (Photo courtesy of NIST.) **Figure 2**

doubt on the depth of this understanding. In particular the group at NIST found that the confinement time of the molasses was optimized when the laser beams were detuned much further from resonance than predicted by the theory. Furthermore, the molasses was degraded by magnetic fields too small to produce Zeeman shifts significant compared with either the detuning or the natural linewidth. These and other disquieting results prompted the NIST team to make more precise measurements of the temperature. They adopted another form of the ballistic technique, measuring the time atoms released from the molasses took to reach a nearby probe region. Thus this time-of-flight method avoided some of the large uncertainties of the earlier technique. The deduced velocity spectrum does not depend as strongly on the details of the original confinement volume. In early 1988 the new technique gave the startling result[9] that the temperature was only 40 μK, much lower than the predicted lower limit of 240 μK. Furthermore, the lowest temperatures were reached with the laser tuned several linewidths from resonance, whereas the theory predicted that the lowest temperature would occur just half a linewidth from resonance.

Such disagreements were at first difficult to believe, especially considering the attractive simplicity of the Doppler cooling theory (and the generally held belief that experiments never work better than one expects). Nevertheless, remeasurements made by the NIST group, using a variety of techniques, and confirming experiments at Stanford[10] and at the Ecole Normale Supérieure in Paris,[11] left little doubt that the Doppler cooling limit had been broken. Furthermore, subsequent experiments[12] showed that the low temperature was not an effect of high intensity. The temperature decreased as the intensity decreased, indicating that the low temperatures occurred in the low-intensity regime where the Doppler cooling theory was expected to work best. This turn of events was both welcome and unsettling. How were these results to be understood?

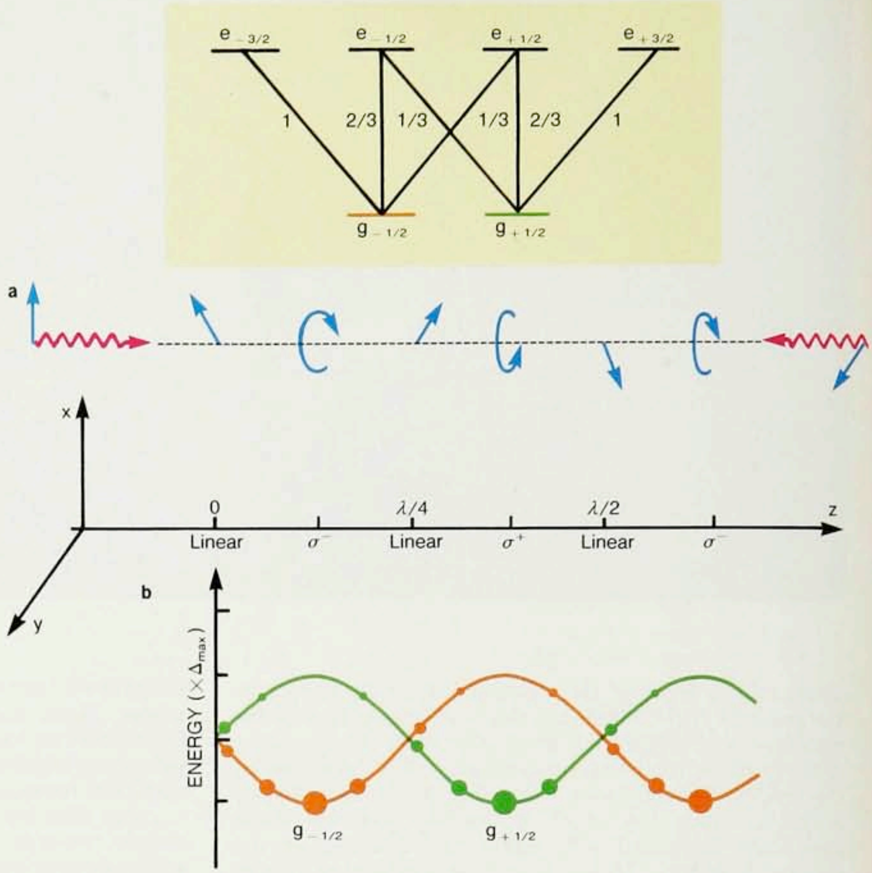
Optical pumping induces new mechanisms

The explanation for the very low temperatures came in mid-1988, when groups at Ecole Normale Supérieure[11] and at Stanford[13] independently proposed new cooling mechanisms. These mechanisms rely upon optical pumping, light shifts and laser polarization gradients. Since then, more quantitative theories have been worked out.[14,15] We will focus here on the key ideas.

The first essential point is that alkali atoms are not simple two-level systems. They have several Zeeman sublevels in the ground state g, which are degenerate in the absence of external fields; they correspond to the different possible eigenvalues of the projection of the total angular momentum on a given axis. These sublevels open the door for such important physical effects as optical pumping, which transfers atoms from one sublevel g_m of g to another $g_{m'}$ through absorption–spontaneous emission cycles. Such cycles occur with a mean rate Γ', which at low laser intensity I_L is proportional to I_L and which can be written as $\Gamma' \sim 1/\tau_p$, where τ_p represents an optical pumping time between Zeeman sublevels. As a result of optical pumping, a particular distribution of populations (and coherences) is reached in steady state among the various sublevels g_m. This distribution depends on the laser polarization.

The optical interaction also induces energy shifts $\hbar\Delta'$ in g, which are called "light shifts."[16] One way of understanding the light shifts is to consider the "dressed" states of the atom–laser field system. Such dressed states have a splitting $|\delta|$ between the atomic ground level with a given number of photons and the excited level with one photon less. The atom–field interaction couples these two states of the atom–laser system with a coupling strength characterized by the Rabi frequency Ω. The interaction causes the two dressed states to repel each other and, for large $|\delta|$, increases the distance between them by $\Omega^2/2|\delta|$. The magnitude of the light shift of the atomic ground level is half of that amount. The Rabi frequency is proportional to the field amplitude, so that the light shifts, like the pumping rate $1/\tau_p$, are proportional to I_L at low I_L. They also depend on the laser polarization, and they vary in general from one Zeeman sublevel to the other.

Another important ingredient of the new cooling mechanisms is the existence of polarization gradients, which are unavoidable in three-dimensional molasses. Because of the interference between the multiple laser



Light shifts in a polarization gradient. (**a**) Counterpropagating laser beams with orthogonal linear polarizations produce a total field whose polarization changes every eighth of a wavelength from linearly polarized to circularly polarized, as shown. An atom with no velocity is put into such a field. The inset shows the energy levels of the atom used in this example. The numbers along the lines joining the various ground and excited-state sublevels indicate the relative transition probabilities. (**b**) The light-shifted energies and the populations of the two ground-state sublevels of this atom. The energies and populations vary with polarization and thus change with the atom's position. The populations are proportional to size of solid circles. **Figure 3**

beams, the laser polarization varies rapidly over a distance of one optical wavelength. Thus both the equilibrium population distribution among the sublevels g_m and the light shift of each sublevel depend on the position of the atom in the laser wave.

Consider a specific simple example of the new cooling mechanisms, using a one-dimensional molasses in which the two counterpropagating waves have equal amplitudes and orthogonal linear polarizations. Such a laser configuration gives rise to strong polarization gradients because the polarization of the total fields changes continuously over one eighth of a wavelength from linear to σ^+ (circularly polarized in a counterclockwise direction as seen from $+z$ axis), from σ^+ to linear in the next $\lambda/8$, from linear to σ^- (clockwise) in the next $\lambda/8$ and so on as one moves along the z axis of the stationary wave (see figure 3a). In order to have at least two Zeeman sublevels in the atomic ground state g, we take the simple case of an atomic transition from the ground state with total angular momentum $J_g = \frac{1}{2}$ to the excited state e with $J_e = \frac{3}{2}$. (See the inset in figure 3.)

Because of the polarization gradients, the populations and the energies of the two ground state sublevels depend strongly on the position of the atom along the z axis. Consider, for example, an atom at rest located at $z = \lambda/8$, the polarization there being σ^- (see figure 3b). The absorption of a σ^- photon can take the atom from $g_{+1/2}$ to $e_{-1/2}$, from which state it can decay to $g_{-1/2}$. (If the atom decays to $g_{+1/2}$ it can absorb another σ^- photon and have another chance to arrive at $g_{-1/2}$.) By contrast absorbing a σ^- photon from $g_{-1/2}$ brings the atom to $e_{-3/2}$, from which it can only decay to $g_{-1/2}$. It follows that, in the steady state, all of the atomic population is optically pumped into $g_{-1/2}$. (We are assuming that the laser intensity is low enough that the excited state population is negligible.) As shown in the inset in figure 3, the σ^- transition beginning on $g_{-1/2}$ is three times as intense as the σ^- transition starting from $g_{+1/2}$. Consequently the light shift Δ'_- of $g_{-1/2}$ is three times larger (in magnitude) than the light shift Δ'_+ of $g_{+1/2}$. (We assume here that the laser is detuned to the red, so that both light shifts are negative.) If the atom is at $z = 3\lambda/8$, where the polarization is σ^+, the previous conclusions are reversed. All the population is in $g_{+1/2}$ and we have now $\Delta'_+ = 3\Delta'_-$. Finally, if the atom is in a place where the polarization is linear, for example in $z = 0$, $\lambda/4$, $\lambda/2, \ldots$, symmetry considerations show that the two sublevels are equally populated and undergo the same light shift. All these results are summarized in figure 3b, which represents as a function of z the light-shifted energies and the populations of the two ground state sublevels for an atom at rest in z.

Clearly the force on an atom at rest spatially averages to zero, because the population is symmetrically distributed around the hills and the valleys. If the atom moves, the symmetry is disturbed, and an average friction force appears. The key point is that optical pumping, which establishes the population distribution, takes a finite time τ_p. Consider, for example, an atom moving to the right and starting at $z = \lambda/8$, where the population is pumped into the bottom of the valley (see figure 4). If the velocity v is such that the atom travels over a distance of the order of $\lambda/4$ during τ_p, the atom will on the average remain on the same sublevel and climb up the potential hill. At the top of the hill, it has the highest probability of being optically pumped to the bottom of the potential valley. From there, the same sequence can be repeated, as indicated by the solid curves in figure 4. Because of the time lag τ_p, the atom, like Sisyphus in Greek mythology, always seems to be climbing potential hills, transforming part of its kinetic energy into potential energy.

The previous physical picture clearly shows that this new cooling mechanism is most effective when the atom travels a distance of the order of λ during the optical pumping time τ_p. Thus the velocity-capture range is defined by $v_p \simeq \lambda/\tau_p$, or equivalently $kv_p \simeq 1/\tau_p$. Because the optical pumping rate is proportional to the laser intensity I_L, the range v_p is also proportional to I_L and tends to zero as I_L goes to zero. This contrasts with the case for Doppler cooling, where the velocity-capture range v_D is independent of I_L. On the other hand the friction coefficient α of the new cooling mechanism remains large and independent of I_L, whereas it was proportional to I_L in Doppler cooling. This important (and rather counterintuitive) property results because when I_L tends to zero, the long optical pumping times compensate for the weakness of the light shifts.

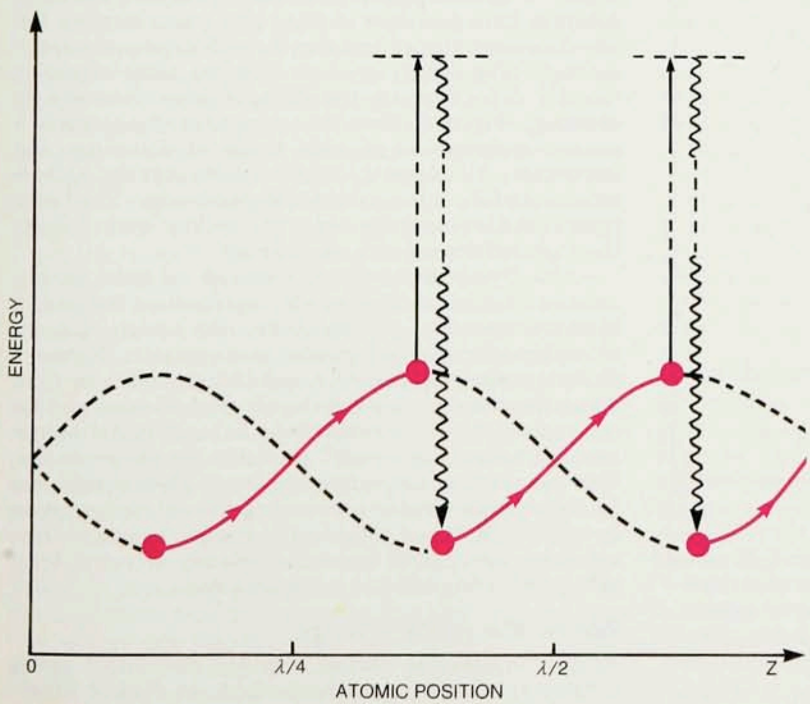
While the friction coefficient α does not depend on the laser intensity, the heating rate does. The temperature to which the atoms are cooled depends on the ratio of the heating rate to the friction coefficient, so the temperature is proportional to I_L. The friction and heating also depend on the laser detuning in such a way that at large detuning the temperature is inversely proportional to δ.

Figure 5 compares in a qualitative way the behavior of Doppler and polarization gradient cooling forces for different intensities. Clearly the Doppler force maintains the same capture range for increasing intensity while the friction coefficient (the slope at $v = 0$) increases. In polarization gradient cooling, on the other hand, it is the friction coefficient that remains constant (and quite large) and the capture range (which may be quite small) that increases. At low velocity, polarization gradient cooling is generally the more effective mechanism. For higher velocities, depending on the laser parameters, the Doppler cooling may be better.

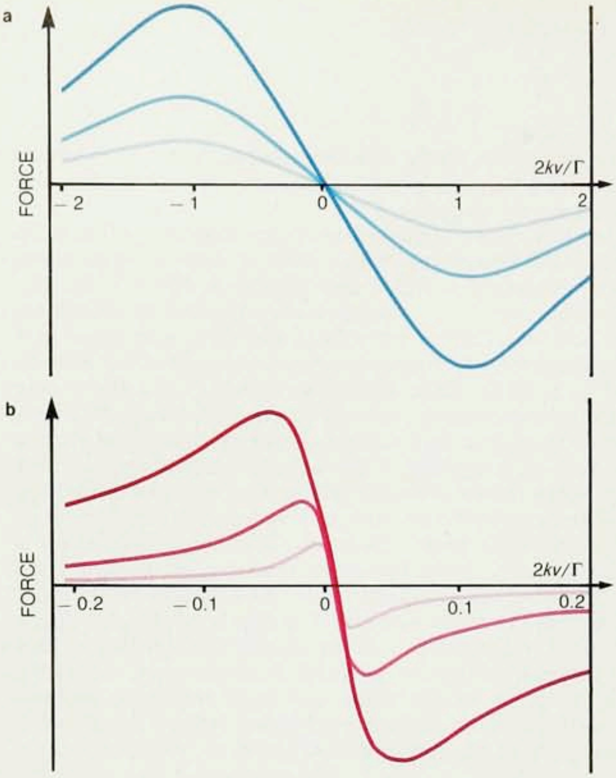
Other laser configurations can produce cooling exhibiting the same properties. Some of these have polarization gradients without any Sisyphus effect. (See, for example the σ^+–σ^- configurations studied in references 14 and 15.) Others use a Sisyphus effect appearing in a standing wave having no polarization gradient but subjected to a weak static magnetic field.[17,18] All these new cooling mechanisms, as well as the one described above, share the following features: When the multilevel atom is at rest at a position z the density matrix $\sigma_{st}(z)$, which describes the steady-state distribution of populations (and coherences) in the ground state, strongly depends on z, on a wavelength scale. Because optical pumping takes a finite time τ_p, when the atom is moving, its internal state $\sigma(z)$ cannot follow adiabatically the variations of the laser field due to atomic motion: $\sigma(z)$ lags behind $\sigma_{st}(z)$ with a delay of the order of τ_p. It is precisely this time lag τ_p that is responsible for the new friction mechanism. The time lag becomes longer when the laser intensity becomes smaller, and the friction mechanism retains its effectiveness even as the intensity is lowered.

Comparing experiment and theory

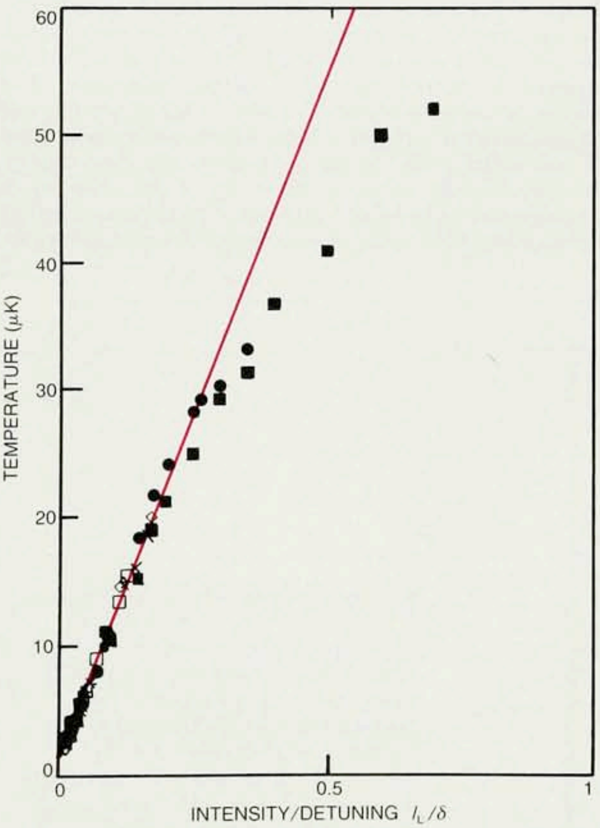
This theory of a new laser cooling force caused by spatially dependent optical pumping, although formulated only in one-dimension, accounted for most of the major features observed in three-dimensional optical molasses. The extremely low temperatures, as well as the dependence of the temperature on laser intensity and on detuning, were all consistent with the predictions of the new theory. Furthermore, the extreme sensitivity of the molasses to the magnetic field could be understood on the grounds that the magnetic field shifts and mixes the Zeeman sublevels,



Forever climbing hills, as did Sisyphus in the Greek myth, an atom that is traveling in the laser configuration of figure 3 moves away from a potential valley and reaches a potential hill before being optically pumped to the bottom of another valley. On the average, the atom sees more uphill parts than downhill ones, and the net energy loss cools it. The effect is near maximum in the special case shown here because the atom travels one fourth of a wavelength in the mean time τ_p that an atom waits before undergoing an optical pumping cycle. **Figure 4**



Damping force in Doppler cooling (**a**) and in polarization-gradient cooling (**b**). Horizontal axes are the normalized velocities $2kv/\Gamma$, where k is the wavevector of the laser beams and Γ is the linewidth of the atomic resonance. Curves are shown for an arbitrary intensity I_0 (dark) and for $I_0/2$ (medium shade) and $I_0/4$ (light). For Doppler cooling, the velocity range over which cooling remains effective is independent of intensity while the friction coefficient (slope of the force curve at $v = 0$) increases with increasing intensities. By contrast, for polarization cooling the velocity range increases for increasing intensities while the friction coefficient stays constant and large. Note the different horizontal scales. **Figure 5**



Temperature depends linearly on I_L/δ, where I_L is the laser intensity and δ is the laser detuning. These experimental results agree with the theory for polarization-gradient cooling. Symbols corresponds to different values of detuning. (Adapted from ref. 20.) **Figure 6**

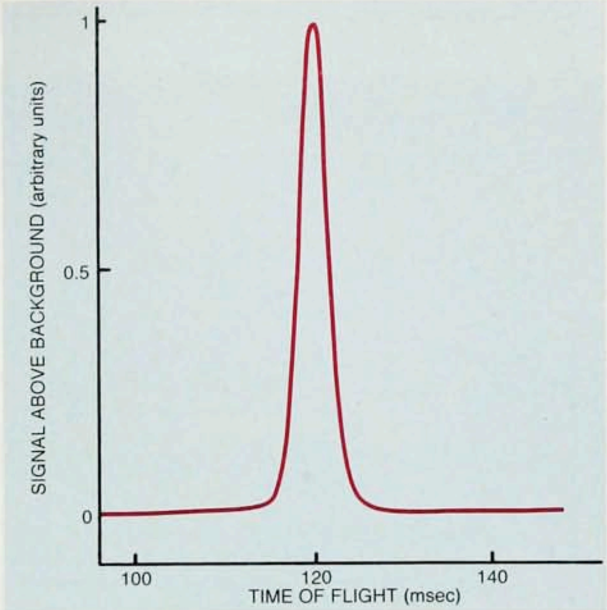
frustrating the cooling mechanism that depends on optical pumping and light shifts of these same levels. The new theory also led to a testable prediction: The magnetic field should inhibit the cooling less at higher laser intensity because the field competes with larger light shifts and optical pumping rates. The confirmation[19] of this new prediction indicated that the theory was at least qualitatively correct. Another positive indication was the observation at Stanford[17] of nonthermal, bimodal velocity distributions, indicating a velocity-capture range smaller than for Doppler cooling. Because the velocity-capture range of the cooling force is proportional to the laser intensity, there will be a nonzero threshold laser intensity for which the cooling works, in contrast to the case for Doppler cooling. The team at NIST qualitatively confirmed the existence of such a threshold.[19]

Although the new cooling mechanism was first found in sodium, this atom has not proved to be an ideal testing ground for the theory. The particular hyperfine spectroscopic structure of sodium prevents the molasses from working as the laser is detuned far from resonance. This large detuning limit is exactly where the theory is simplest and least dependent on the details of the polarization gradients. Experiments at the Ecole Normale Supérieure using cesium, which has a much larger hyperfine structure, have been able to explore the large detuning limit and show striking agreement between the one-dimension theory and the three-dimensional experiments.[20] The theory predicts that the temperature is linearly dependent on the ratio of laser intensity to detuning. Figure 6 shows the temperature for atoms in a cesium molasses for a wide range of detunings and intensities. All except the smallest detunings and highest intensities follow the expected dependences. The lower limit to the intensity for which the cooling works follows the expected dependence on detuning.

The lowest temperature obtained in these experiments on cesium is 2.5 ± 0.6 μK, representing the coldest kinetic temperature yet reported for any sample of atoms in a three-dimensional cooling arrangement. Figure 7 shows a typical experimental time-of-flight spectrum from which this temperature is deduced. Carl Wieman and his colleagues at the Joint Institute for Laboratory Astrophysics have recently observed[21] similarly low temperatures. This temperature for cesium and the 25-μK temperatures for sodium measured in a three-dimensional configuration by the NIST[19] and Stanford[17] groups represent rms velocities just a few times the velocity of recoil from absorption or emission of a single photon.

Below the recoil energy

In all the previous cooling schemes, the cooled atoms constantly absorb and reemit light, so that it seems



Time of flight distribution for cesium atoms that were released from an optical molasses and traveled 7 cm from there to a probe. The curve implies a temperature of 2.5 μK, a record low temperature. (Adapted from ref. 20.) **Figure 7**

impossible to avoid the random recoil due to spontaneously emitted photons. The fundamental limit for laser cooling is therefore expected to be on the order of $E_{rec} = \hbar^2 k^2/2M$, where M is the atomic mass. Actually, this limit does not always hold: At least in one-dimension, the recoil limit can be overcome with a completely different cooling mechanism that was demonstrated in 1988 by the group at the Ecole Normale Supérieure.[22]

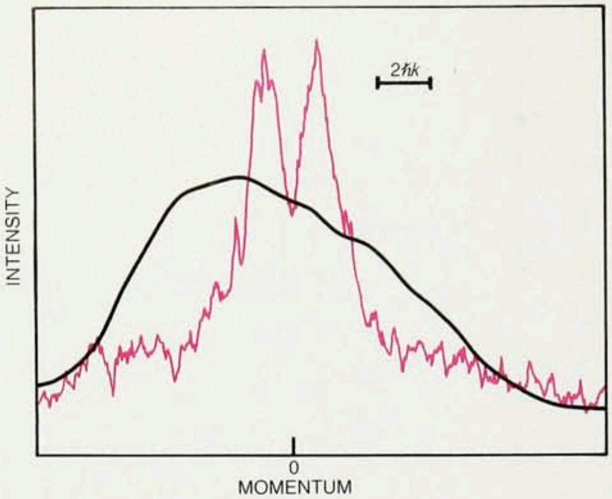
This new mechanism is based on "velocity-selective coherent population trapping." Coherent population trapping means that atoms are prepared in a coherent superposition of two ground state sublevels that cannot absorb light; the two absorption amplitudes starting from these two sublevels have completely destructive interference with each other. Once the atoms are optically pumped into such a trapping state, the fluorescence stops. This well-known phenomenon was observed[23] for the first time at the University of Pisa in 1976. The team at the Ecole Normale Supérieure in 1988 introduced the new trick of making the trapping state velocity selective and therefore usable for laser cooling. They accomplished this with a one-dimensional molasses where the two counterpropagating laser beams had opposite circular polarizations. One can show that the trapping state exists only for atoms with zero velocity.[22,24] If $v \neq 0$, the interference between the two transition amplitudes starting from the two ground state sublevels is no longer completely destructive and the atom can absorb light. The larger v is, the higher the absorption rate. The challenge of course is to populate the nonabsorbing trapping state.

The idea is to use the atomic momentum redistribution that accompanies an absorption–spontaneous emission cycle: There is a certain probability for an atom initially in an absorbing velocity class ($v \neq 0$) to be optically pumped into the $v = 0$ nonabsorbing trapping state. When this happens, the atoms are "hidden" from the light and so protected from the random recoils. Thus they remain at $v = 0$. Atoms should therefore pile up in a narrow velocity interval δv around $v = 0$. Atoms for which v is not exactly 0 are not perfectly trapped: As a result the width δv of the interval around $v = 0$ is determined by the interaction time Θ. For a given Θ the only atoms that can remain trapped are those for which the absorption rate times Θ is smaller than 1. Since the absorption rate increases with v, the larger Θ, the smaller v for the remaining atoms. There is no lower limit to the velocity width that can be reached by such a method, provided of course that the interaction time can be made long enough. This kind of cooling differs from all the previous cooling mechanisms in that friction is not involved. Instead, the cold atoms are selected by a combination of optical pumping and filtering processes that accumulate them in a small domain in one-dimensional velocity space.

The discussion so far has been oversimplified. A more careful analysis,[22,24] using a quantum description of the atomic translational degrees of freedom along the direction **z** of the two counterpropagating laser waves, shows that the trapping state is a linear combination of two atomic states differing not only by the internal Zeeman quantum number but also by the momentum quantum number p along **z**. The trapping state is therefore a double momentum state. Indeed, the experimental results obtained at Ecole Normale Supérieure for the momentum distribution along **z** of helium-4 atoms cooled by this method[22] exhibit a double-peak structure (see figure 8), as predicted theoretically. The width of each peak is smaller than the photon momentum, $\hbar k$, which verifies that velocity widths have gone below the recoil limit. The one-dimensional temperature (determined by the component of velocity along the laser axis) corresponding to these observed widths is of the order of 2 μK. Possible two-dimensional extensions,[24,25] as well as three-dimensional extensions[25,26] of this cooling scheme have been recently proposed, leading to trapping states that are linear combinations of several momentum eigenstates whose momenta point in different directions, but all have the magnitude $\hbar k$.

A combination of known effects

In conclusion we would like to stress that the new physical mechanisms that have made it possible to cool atoms to the microkelvin range are based on physical effects, such as optical pumping, light shifts and coherent population trapping, that have been known for a long time. For example, the first observation of light shifts[27] predates the use of lasers for atomic spectroscopy: Kastler called them "lamp shifts" in a word play indicating that they were produced by light from a lamp. The researchers of 30 years ago fully realized that the differential light shifts of the ground state Zeeman sublevels depended strongly on the polarization of the light. The use of optical pumping to



Distribution of atomic momenta in the direction of the laser beam for helium-4 atoms cooled by the velocity-selective coherent-population trapping method (red). The width of each peak is less than the momentum $\hbar k$ of a single photon, indicating cooling below the recoil limit. The uncooled atomic momentum distribution is shown in black. (Adapted from ref. 22.) **Figure 8**

differentially populate Zeeman sublevels is even older. For us it has been especially appealing to see such well-known physical effects acquire new life as they conspire in quite unexpected ways to cool atoms to the lowest kinetic temperatures ever measured.

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