Bound by Light

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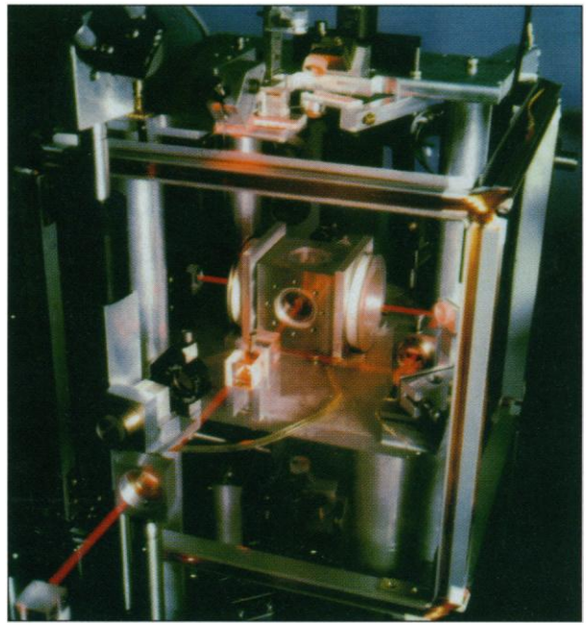
In the 1970s, it was proposed that a periodic potential produced by light waves could be used to create a stable crystal-like structure in an atomic gas (*1*). Atoms in these "crystals" would be confined to regions much smaller than the optical wavelength. Thus, these crystals can produce substantial density enhancements over the initial atomic gas. This kind of crystal formation also includes strong cooling processes, so the phase-space density enhancements can be enormous. Crystals in two and three dimensions should offer increases in phase-space density of orders of magnitude compared with simple one-dimensional crystals because the atoms are confined to smaller volumes. In addition, three-dimensional crystals should offer huge lifetime enhancements because there would be no spatial escape route for the confined atoms. These large densities of cold confined atoms should provide many opportunities for enhanced fundamental measurements of atom-field interactions, as well as atom-atom interactions among cold atoms separated by less than an optical wavelength. In addition, such periodic lattices may set the stage for the study of myriad quantum statistical effects in many-body systems. Two-dimensional crystallization of atomic gases may also have important technical applications to lithography, where the creation of narrow ordered structures is of particular importance (*2*).



Optical foundry. "Crystals" of ultracold rubidium atoms are formed inside this vacuum chamber **(center)** as they fall into microscopic optical traps produced by carefully coordinated laser beams. The red light from a helium-neon laser is a tracer that shows the light path of the barely visible 780-nm trapping light from a diode laser [Courtesy T. W. Hänsch, University of Munich]

The hopes generated by these many exciting possibilities were dashed when further calculations showed that crystallization of two-level atoms in one-dimensional standing waves will not occur because optical heating would produce an equilibrium kinetic energy that is at least of the order of the depth of the optical potential well (*3*). Thus, two-level atoms will not form long-lived ordered crystals. These calculations did not, however, apply to atoms with more than two levels, and experiments showed that multilevel atoms are confined in three-dimensional optical potentials with sizes of the order of an optical wavelength (*4*). These observations caused a great renewal of interest in the possibility of creating optical crystals, with atoms confined to regions much smaller than a wavelength.

The mechanism by which atoms are optically trapped has a long history. As Ashkin pointed out (*5*), at low intensities the optical potential for a two-level atom is equal to the light shift, which is in turn proportional to the intensity. Thus a weak standing-wave light field results in a sinusoidal potential with a period of half of the optical wavelength l. Later experiments showed that atoms with more than two levels form one-dimensional optical crystals (*6*). This crystallization occurs because multilevel atoms have additional cooling processes associated with polarization gradients, which allowed equilibrium kinetic energies below the limit for two-level atoms. In particular, it allows equilibrium kinetic energies much lower than the depth of the optical potentials, so a stable periodic atomic lattice will be created by the light (*6*). Detailed experiments demonstrated one-dimensional crystallization in good agreement with these theories (*7*). The extension to two dimensions is complex and subtle and has recently been demonstrated in two very elegant experiments: one by Hemmerich and Hänsch at the University of Munich (*8*) and a second by Grynberg *et al.* at the Ecole Normale Superieure in Paris (*9*). Both experiments used polarization gradient cooling to achieve temperatures low enough for stable trapping.

To understand polarization gradient cooling, it is useful to note that for a weak field, the light-induced Stark shift between two atomic levels a and e is proportional to the square of the Rabi frequency, $|\Omega_{ae}|^2 = |\mu_{ae} \cdot \mathbf{E}|$ where μ_{ae} is the dipole matrix element between states a and e, and $\mathbf{E}$ is the electric field vector due to the light. For a two-level system in a one-dimensional standing wave, this is just proportional to the intensity, but for a system with a polarization gradient, the light shift can change with the direction of the electric field vector, even if its magnitude remains constant.

In the weak-field limit, where coherences can be ignored, the total energy shift of an atom with a ground state angular momentum J and an excited state angular momentum J' is proportional to the weighted sum of energies of the magnetic sublevels of the ground state, given by

$$\sum_{m_j} \sum_{m_{j'}} \rho_{m_j,m_j} |\Omega_{m_j,m_{j'}}|^2$$

where ρ_{m_j,m_j} is the population of ground state sublevel m_j. Thus, a moving atom can convert kinetic energy to potential energy if either ρ or $|\Omega|^2$ depends on position, even if the magnitude of $\mathbf{E}$ is spatially invariant. An atom will be cooled if its kinetic energy is converted to potential energy with respect to the field and then makes a spontaneous transition to a ground state with a lower potential energy. This is the basic mechanism underlying polarization gradient cooling. In one-dimensional demonstrations of polarization gradient cooling, two weak counter propagating fields of opposite polarizations form a light field with a polarization gradient that produces cooling. If the two counter propagating fields have opposite circular polarizations, then the Stark shifts of the ground states are independent of position. The atoms are cooled by optical pumping into the local $m_j = 0$ ground state, where the local quantization axis for the atom is parallel to the electric field vector at each point, so the light is always π polarized. The $m_j = 0$ state has the lowest potential energy due to the Stark shift induced by the π light. This cooling can be understood by considering an atom which starts at a position $x = 0$. As the atom moves away from this point to $x + dx$, its state, which was $m_j = 0$ at $x = 0$, is now a superposition of the m_j states, which have higher energies, so the atom has converted kinetic energy to potential energy. Optical pumping will try to move all of the population to the $m_j = 0$ state at the new position $x + dx$ and in so doing will radiate away the potential energy, resulting in cooling. Thus,

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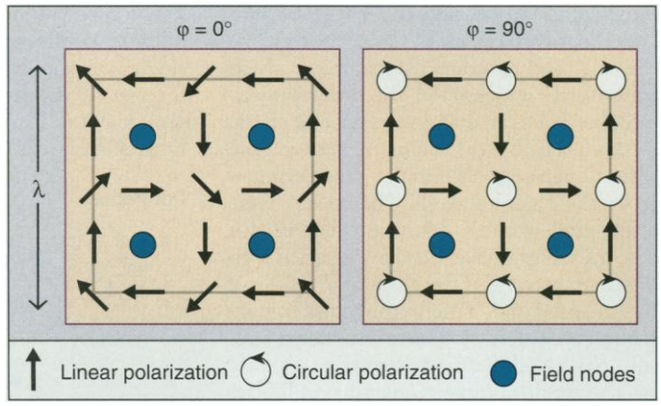
the cooling in this case is associated only with changes in ρ because $|\Omega|^2$ are invariant. In addition, there is no crystallization because the Stark shifts are independent of position.

By contrast, if the two counter propagating fields have opposite linear polarizations, then there are spatially dependent Stark shifts which can trap atoms. The origin of these trapping potentials can be derived from an analysis of the polarization as a function of position. The polarization of the total field is linear when there is zero phase shift between the two counter propagating traveling waves, whereas the total polarization is circular when the accumulated phase shift is $\pi/4$. The phase difference between the two fields goes as $2z(2\pi/\lambda)$, so the distance between fields of the same circular polarization is $\lambda/2$, but opposite circular polarizations are separated by $\lambda/4$.



Setting an optical trap. Two optical standing-wave fields are created in the x and y directions, with a phase difference φ. The polarization gradients for different values of φ lead to optical arrays of light traps. For $\varphi = 90$, the atoms are trapped in a two-dimensional array at the points where the polarization is circular. [Reprinted from (*8*) with permission]

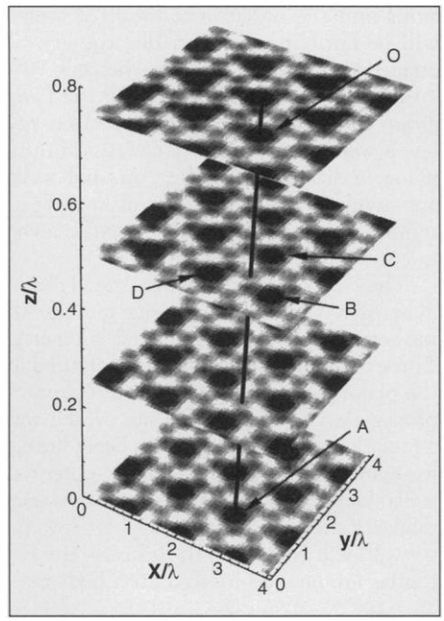
An atom in the $m_j = J$ state has its potential minimum where the Stark shift for that state is a maximum, which occurs where the field is σ_+ polarized. Thus, the $m_j = J$ ground state sublevel has potential minima separated by $\lambda/2$. Similarly, the potential minima for the $m_j = -J$ sublevel occur where the light is σ_- polarized. These potential minima are separated from each other by $\lambda/2$, and offset from the $m_j = J$ minima by $\lambda/4$. Thus, there are four potential minima per optical wavelength. Polarization selection rules will result in the atoms being optically pumped into the ground state with the minimum energy, so atoms are trapped near potential minimum. Thus, atoms trapped at neighboring field antinodes have opposite values of m_j, which is similar to an antiferromagnetic medium.

Recent detailed experiments have shown that in one-dimensional systems, atoms can be confined to the lowest quantum states of these periodic optical potentials. The spatial distributions of atoms in these wells was very narrow, approximately 1/15 of an optical wavelength (*6*). One might imagine that a similar two-dimensional confinement could be obtained by simply creating a similar potential in two dimensions, x and y; however, the situation is more complicated because there is an additional parameter in the two-dimensional case: the phase difference, φ, between the field in the x direction and the field in the y direction.

Hemmerich and Hänsch have successfully observed two-dimensional crystallization of rubidium atoms using two optical standing waves oriented along the x and y axes and linearly polarized in the xy plane (*8*). In contrast with the one-dimensional case, the intensity here is not spatially invariant but has maxima and minima, where successive maxima are separated by $\lambda/2$. When $\varphi = 90°$, then polarization alternates between linear and circular, as in the case of opposite linearly polarized beams in one dimension; however, in the two-dimensional case the spacing between opposite linear circular polarization is $\lambda/2$ not $\lambda/4$ in the one-dimensional case. As in the one-dimensional case, atoms in the $m_j = J$ state will be trapped near the positions where the light is σ_+ polarized, $m_j = -J$ state will be trapped near the positions where the light is σ_- polarized. As in the one-dimensional case, atoms trapped at neighboring field antinodes have opposite values of m_j, so the crystal is a two-dimensional antiferromagnetic medium.

This trapping was observed by measuring the absorption from a weak probe beam. For $\varphi = 90°$, the measurements of the Munich group showed that the spacing between the ground state and the first excited state was 159 kHz, in good agreement with the theoretical value of 161 kHz, obtained by modeling the potential well as a two-dimensional simple harmonic oscillator. In addition, the measurements indicate that the population in the ground state of these two-dimensional wells was approximately four times the population in the first excited state.

In contrast, when $\varphi = 0°$ the atoms are not nearly as well localized. For $\varphi = 0°$, the light is linearly polarized everywhere, which is similar to the one-dimensional case of opposite circular polarization, except for the intensity variation which was absent in one dimension. In this case, the potential minima occur at the intensity maxima, where the Stark shift for each of the ground state sublevels is a maximum. The trapping in this case is attributable only to the intensity gradient, in contrast with the $\varphi = 90°$ case where the trapping was dominated by the polarization gradient. In addition the polarization gradient cooling is not as strong as in the $\varphi = 90°$ case; consequently, the localization is less pronounced in the $\varphi = 0°$ case than in the $\varphi = 90°$ case.



Three-dimensional molasses. Optical cesium crystals in three dimensions were created by aligning the lasers along the threefold symmetry axes of a tetrahedron. Figure shows the minima of the optical potential (dark zones). The minima lie on a body-centered-cubic lattice at points of postive circular polarization. [Reprinted from (*9*) with permission]

The two-dimensional version of the Munich experiment depended strongly on phase relationship between the two perpendicular standing waves. By contrast, there was no phase dependence in the Paris experiment, which demonstrated crystallization of cesium atoms using three traveling waves at 120° to one another. For the three-beam case, the potentials are independent of the relative phases of the three traveling waves. Changes in the phase relations simply result in translations of the potentials in space, rather than changes in the potential depth (as in the case of the two standing waves that can be decomposed into four traveling waves). The Paris group cites the more general result that whenever an optical molasses is composed of p beams in an n-dimensional space, then phase shifts will be equivalent to spatial translations as long as $p = n + 1$.

For the three traveling-wave geometry in two dimensions the potential minima are located at the points where the total field is circularly polarized. These points form a hexagonal lattice. In this pattern σ_+ polarized potential wells alternate with σ_- polarized wells, so atoms in neighboring potentials have opposite angular momentum direc-

tions and the ordering of localized atoms will be antiferromagnetic, like the crystal created by the Munich group when $\varphi = 90°$. Absorption probe experiments by the Paris group showed that the vibrational energy levels were independent of direction in the plane, indicating that the potential wells are circularly symmetric. The measured potential depths varied as $\sqrt{Intensity/Detuning}$ in good agreement with theory.

The Paris group also demonstrated three-dimensional crystallization using four traveling-wave fields in a tetrahedral geometry. Three of the fields were linearly polarized in the plane perpendicular to the direction of propagation of the fourth beam, which was circularly polarized. The fourth beam breaks the symmetry between σ_+ and σ_- potential wells due to the other three beams. In particular, if the fourth beam is σ_+ polarized, the σ_+ wells will be deeper. In this case, the potential minima are located on a body-centered-cubic lattice, and the trapped atoms are primarily in the $m_j = J$ state. Thus, unlike the one- and two-dimensional cases which were antiferromagnetic, the three-dimensional crystal is analogous to a ferromagnetic medium. The broken symmetry between the three dimensions also results in an asymmetry in the potential wells. The crystals were again probed using absorption, but in this case the vibrational energy levels varied with direction because of the ellipsoidal shapes of the potential wells. Finally, the Munich group reports that they also have preliminary results of three-dimensional crystals.

The wealth of experimental possibilities created by these two- and three-dimensional crystals is yet to be explored. The density limits and role of atom-atom interactions are still unknown. In addition, transferring this two-dimensional order to a solid surface would present considerable experimental challenges, but may offer very narrow dots that can be used for lithography. The possibility of confining several cold atoms in a single potential offers the hope of observing interesting collective effects and may present a suitable system for observing Bose-Einstein condensation.

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A New Twist on Integrins and the Cytoskeleton

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The movement, shape, and polarity of cells depend on the close cooperation of proteins outside the cell [the extracellular matrix (ECM)], proteins on the surface of the cell (cell adhesion molecules, that is, integrins), and proteins inside the cell (the cytoskeleton). In this issue of *Science*, an elegant biophysical study by Wang and co-workers (*1*) confirms a mechanical connection among ECM components, integrins, and the cytoskeleton, which are responsible for changes in cell form and function. Indeed, their new result suggests that integrins are part of a group of cooperating molecular elements that are organized according to tensegrity (tensional integrity) architecture, the building concept of R. Buckminster Fuller that underlies geodesic domes.

Cultured cells lose their characteristic flattened shape and become round when their adhesion to the culture dish is loosened by the protein degrading enzyme trypsin or when their cytoskeleton is disrupted by drugs. Current thinking about this interplay between cell adhesion and the cytoskeleton is strongly influenced by the structure of focal adhesions (*2*). These regions of very close contact (approximately 15 nm) between the plasma membrane of cells and their underlying substratum appear to represent direct mechanical linkages from the outside to the inside of the cell. In the now classic model, proteins of the ECM, including collagen, laminin, and fibronectin, bind to the extracellular region of a plasma membrane receptor, an integrin. Integrins are a superfamily of integral membrane proteins that are heterodimers of α and β subunits (*3*). Many integrins have an affinity for the amino acid sequence arginine-glycine-aspartate (RGD) in their ECM ligand. The integrins also have a small cytoplasmic region that binds to elements of the actin cytoskeleton: Immunofluorescent images of focal adhesions show co-localization of integrins with the termini of actin bundles and with actin-binding proteins. Also, integrins bind in vitro to actin-binding proteins such as talin and α-actinin (*2*, *3*).

These biochemical studies have been advanced considerably by the work now reported by Wang and co-workers. They have used a sophisticated application of magnetometry, a method for investigating the mechanics of cells and cytoplasm that goes back at least as far as Crick's only (I believe) experimental report (*4*). Magnetic microbeads were coated with different ligands and used in combination with external magnetic fields to exert controlled mechanical stresses on integrin receptors without changing the shape of the cell. For example, beads coated with synthetic RGD peptides or antibody to the b_1 integrin subunit would be expected to bind specifically to integrins, whereas beads coated with acetylated low density lipoprotein (LDL) or bovine serum albumin (BSA) would bind to other membrane proteins not involved in cell adhesion. The beads were allowed to attach to capillary endothelial cells in culture dishes. Earlier experiments from the same lab showed that fibronectin, an RGD-containing ligand for several integrins, regulates the assembly of these cells into blood vessel–like tubes (*5*). The attached ferromagnetic beads (which remain magnetized after withdrawal of an external magnetic field) were magnetized in a uniform dipole orientation by application of a strong, very brief, homogeneous magnetic field. A second, longer and weaker homogeneous magnetic field was then applied perpendicular to the first, thus producing a mechanical twisting force. The extent of bead rotation was measured by an in-line magnetometer that detected the original magnetic field vector that persisted during twisting. In the absence of any mechanical restraints on the beads, the second pulse would be expected to completely reorient the beads to the new magnetic field, that is, twist the beads through 90° and completely eliminate the original magnetic field vector. Indeed, beads coated with BSA or LDL twisted nearly this much. In contrast, beads coated with RGD peptide or antibodies to integrin twisted through less than 30° at the highest reported forces, indicating a significant mechanical constraint on the twisting of integrin-bound beads. The constraint is evidently due to cytoskeletal linkages to integrins. Addition of poisons directed against the three principal cytoskeletal filaments—microfila-

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