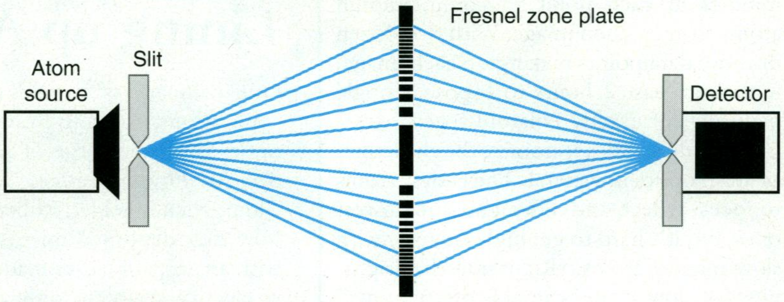
Optics' New Focus: Beams of Atoms

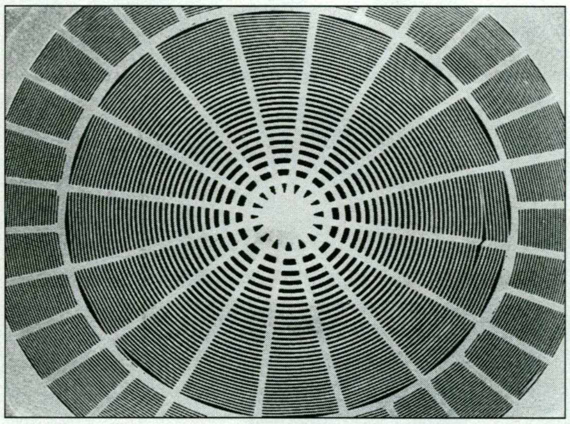
Physicists who manipulate atoms like beams of light have created a whole new field that is likely to have big payoffs

THE EQUIPMENT IN DAVID PRITCHARD'S LAB at the Massachusettes Institutes of Technology would sound familiar to any high school physics student who has finished the lab segment on optics: lenses, mirrors, diffraction gratings. There's even an interferometer—the same kind of device used more than 100 years ago in the famed Michelson-Morley experiment to show that the speed of light is the same in all directions. But the familiar names hide some distinctly unfamiliar features: microscopic grids like tiny picket fences with pickets only a fraction of a micron wide, lasers reflected back on themselves to form standing waves of light, and circular gratings formed of hundreds of concentric rings. These paraphernalia are designed to control not light beams but something much more challenging: beams of atoms.

Pritchard, an atomic physicist, is one of a small but growing group of researchers who are creating a new field analogous to classical optics; they call it "atom optics." The analogy isn't a casual one. Pritchard and his colleagues are subjecting beams of atoms to all the familiar manipulations of optics: focusing them, reflecting them, diffracting them, and even combining diffracted beams to create interference patterns. Until a year or two ago, Pritchard says, these experiments were "just a collection of demonstrations." But they have begun to add up to a new field now that researchers are starting to string together multiple devices into working systems capable, for example, of making atomic "photographs" of simple structures.

None of this is easy—an atom lens takes months to build, and even then it doesn't focus atoms as efficiently as a toy magnifying glass from a Cracker Jacks box focuses light. But the potential rewards make it all worthwhile. Atom optics may eventually yield microscopes that see nanometer-sized details without damaging the specimen, provide ways to measure atomic properties with unprecedented precision, and allow ultra-accurate measurements of acceleration and gravity—valuable, perhaps, in guidance systems for airplanes and rockets or in prospecting for oil. One potential application could even help the semiconductor industry continue to squeeze more and more transistors onto computer chips: Atoms focused into razor-sharp beams might be used to "write" circuit patterns 10 times finer than is now possible with state-of-the-art technology (see box).





Atom camera. *A beam of helium atoms "illuminates" a slit, then is brought to focus at a detector that records an image of the slit. The micrograph shows the structure of the "lens": a .21 millimeter zone plate.*

MLYNEK

SOURCE: MLYNEK *ET AL*./*PHYS. REV. LETT.* ILLUSTRATION: D. DEFRANCESCO

At first glance, the idea of manipulating atoms like light seems fantastic. Optics is, after all, based on the wave nature of light, whereas atoms are usually thought of as bundles of particles—tiny "solar systems" with electrons orbiting a core of protons and neutrons. But quantum physics insists that all matter has a wave nature to complement its particulate quality. Physicists have long exploited this duality to make electron microscopes, which focus beams of electrons to obtain images of objects hundreds of times smaller than can be seen with optical microscopes. Neutrons have been used in a similar way.

Atom optics is the natural next step. Atom beams are much trickier to control than electron beams—atoms are heavier and don't have the charge that makes electrons easy to steer with electromagnetic fields—but atomic physicists have slowly built up the tools and techniques needed to manipulate them. This growing control was demonstrated dramatically last year when Jürgen Mlynek and his colleagues at the University of Konstanz in Germany used an atom lens to focus a beam of helium atoms and make a crude image. Their experience, which they described in the 2 December *Physical Review Letters*, is not likely to make anyone want to trade in a Nikon or Polaroid for an atom camera.

The "scene" that the group captured with its camera was simply a single slit or a pair of slits through which the atoms passed on their way to the camera's lens. The lens, too, would be alien to most photographers. A glass lens can't focus atoms; quite the contrary, it stops them dead. So the Konstanz group resorted to a focusing device called a Fresnel zone plate. The zone plate (a device originally invented to focus light) is a collection of concentric rings that alternately block a beam or allow it to pass. Whereas an ordinary lens works by refraction, or the bending of light as it passes from one substance to another, the Fresnel zone plate relies on diffraction—the spreading out of a wave as it passes through a small opening. The concentric rings of the Fresnel zone plate are carefully spaced so that the diffracted waves add up constructively along a "focal plane" on the other side of the lens.

To read the image formed by the Fresnel zone plate, the group used a movable detector to record the intensity of the atom beam at a series of points in the focal plane. The resulting images were not things of great beauty, but they were recognizable—the photograph of the single slit was a single rounded peak, and the double slit was imaged as a pair of humps.

The main difficulty in the experiment was getting enough helium atoms in the beam to "illuminate" the subject, says Tycho Sleator, a member of the Konstanz team who is spending the spring semester at New York University. The entire apparatus had to be kept in a vacuum chamber, since collisions with air molecules would have deflected the helium beam. But since the size of the vacuum chamber was limited, the Fresnel zone plate had to bring the atom beam to a focus in a short distance—less than a meter—which limited the "brightness" of the beam. In addition to choosing helium atoms, which can be focused in a short distance because they are light, the researchers cooled the beam to slow down the atoms and make them easier to deflect. Doing so, however, meant that fewer atoms would be passing through the slits to be focused and imaged at any given time. As a result, the detector had to be held for 5 minutes at each point to count enough atoms to get a good image. With two dozen or more data points making up each image, it took at least 2 hours to expose a single picture—not exactly Polaroid-speed.

These difficulties epitomize the challenges of atom optics in general. The easiest atoms to focus, reflect, and diffract are the slowest ones, but it's hard to get high intensity with slow-moving atoms. "Right now the brightness [of slow atom beams] is pretty puny," Pritchard says. Then there's the limitation of having to carry out experiments in a high vacuum, and the fact that "we don't have any glass for atom beams," Pritchard says—no obvious way to make efficient atomic lenses and mirrors.

There's ample incentive to overcome such difficulties, however. A microscope that used atoms in place of light would have a much greater resolving power, since the wavelength of atoms in a typical atomic beam can be a fraction of an angstrom, compared to the 4000- to 7000-angstrom wavelength of visible light. In principle, an atom microscope could pick out details smaller than the width of a single atom (although fundamental limits other than that of wavelength may limit the resolving power). Electron microscopes are already capable of revealing details on that scale—but only when the electrons have very high energies and hence are liable to damage the samples. And because atoms, unlike photons and electrons, have an internal structure that is affected by their interactions with other matter, an atomic microscope could reveal features of a sample that light and electron microscopes are oblivious to.

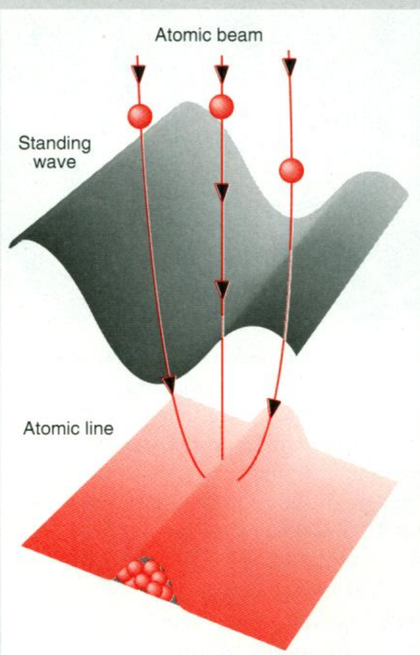
The first step toward an atomic microscope is to make a better lens. The Fresnel zone plate used by the Konstanz team was a commercial model intended for x-ray microscopy; other groups are already building zone plates designed explicitly for atom optics. Pritchard's group, for instance, has made a cylindrical zone plate—one that focuses in one dimension instead of two—and Don Tennant at AT&T Bell Labs recently etched a Fresnel zone plate out of silicon. The silicon lens is not only much more durable than the fragile gold lens used by the Konstanz group, but it should also be able to focus images down to half the size possible with the commercial lens. For a given focal length, the focusing power of a zone plate depends on the number of concentric rings, and semiconductor fabrication techniques can etch silicon zone plates with many more rings than the Konstanz grating has.

Several groups, including those at MIT and Konstanz, are trying a more dramatic approach, focusing atoms with something much more ephemeral than a zone plate—light. They take advantage of a phenomenon scientists have exploited for years, namely light's ability to exert a force on atoms when the frequency of the light is close to one of the specific frequencies that the atom can absorb. The best-known illustration is probably the ability of lasers to slow down atoms and pin them in one spot (*Science*, 11 June 1990, p. 1076). In the early 1980s, Pritchard and co-workers showed how to exploit the

Lining up Atoms With Laser Light

One hallmark of a field that is coming of age is the blossoming of practical applications. Judging from work done recently at AT&T Bell Laboratories, atom optics is on the verge of adulthood. In a paper that appeared in the 28 February *Applied Physics Letters*, Mara Prentiss and Karl Berggren of Harvard and Greg Timp, Nick Bigelow, Robert Behringer, and J.E. Cunningham of Bell Labs describe how they deposited microscopic lines of atoms onto a substrate by focusing them with an array of lenses made of light waves, a technique that may allow the building of electronic circuits only a tenth the size of today's state of the art.

The technique takes advantage of a phenomenon that other researchers have been exploiting to create atomic lenses (see main text): When a beam of light is reflected back on itself, it creates a standing wave that consists of a fixed series of wave peaks and troughs. Each crest and trough can focus atoms if the light is tuned near to a frequency that the atoms absorb. The Bell Labs group used such a standing wave as "an array of [one-dimensional] lenses spaced every half wavelength," Timp says.



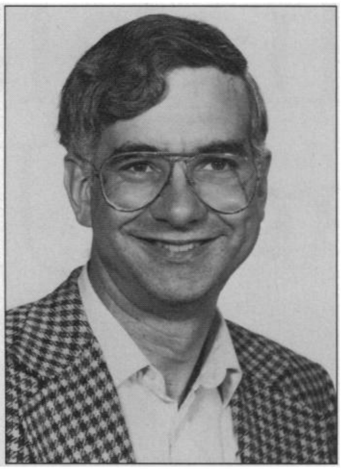
Turning the tables. *Light acts as a lens for matter—a beam of atoms.*

The researchers reflected a laser beam back and forth between two mirrors to create a standing wave parallel to a silicon surface, and then directed a beam of sodium atoms through the standing wave. The result: The sodium atoms were focused into a set of tens of thousands of narrow lines when they hit the silicon surface. The lines of atoms were just 300 nanometers apart (half the wavelength of the laser light used), and the Bell Labs team calculates that the individual lines were only about 10 nanometers across, or just a few atom-widths—much narrower than can be achieved with today's best semiconductor lithography techniques.

The experiment could be the first step toward manufacturing thousands of electronic devices on a single chip, each with line widths of only a few tens of nanometers, the Bell Labs researchers say. By moving the mirrors and thereby shifting the standing wave pattern, they could inscribe several different sets of lines on the surface; by sending the beam through two perpendicular standing waves, they could create an array of dots instead of lines. Two or more different types of atoms could be put down simultaneously in different patterns by using two different standing waves, each tuned near the characteristic frequency of the desired atom. And combined with molecular beam epitaxy, which deposits thin films of material one atomic layer at a time, the atom beams could build up the kind of nanometer-scale, three-dimensional circuitry needed to put a supercomputer on a chip. ■ R.P.

same effect to create a diffraction grating for atoms: Reflecting a laser back and forth between two mirrors creates a "standing wave" of light with "peaks" and "troughs" that stay fixed in space. When an atom beam is aimed through such a standing wave, the atoms are either attracted to or deflected from the wave's maxima and minima, depending on the specific frequency of the laser. Either way, the effect is the same as a physical grating—the beam comes through concentrated in a series of narrow lines.

MIT



Each peak and trough is actually acting as a tiny lens. Ordinarily, such lenses would be far too small to isolate or use individually, but in a soon-to-be-published paper, the Konstanz group describes an inspired strategy for dissecting out a single lens from the standing wave. By bouncing a laser off a glass surface at a very small angle, they created standing waves, aligned parallel to the surface, that were some 20 microns from peak to trough—nearly 100 times the laser's normal wavelength.

The spacing was so large, in fact, that the Konstanz group was able to isolate one "valley" of the standing wave to make a lens. They formed a small slit, about 1 millimeter wide and 25 microns high, and placed it with its long axis parallel to the surface, centered on a trough. When a beam of atoms passed through the slit and into the trough, light forces caused the atoms to converge. The wave was acting only as a cylindrical lens, concentrating the beam into a line instead of a point, but that was enough to enable Mlynek's group to take a "photograph" of a single slit in a manner similar to the Fresnel zone plate experiment. What's more, it should be possible to combine two of the laser lenses to make a normal lens, Sleator says. If one lens focused in, say, the vertical direction and the second in the horizontal, the combination would be a full-fledged laser lens for atoms.

A third type of atom lens was created by researchers at the University of Amsterdam in 1989. The principle is the same as the focusing of light by the curved mirror at the base of a telescope or the reflector in a flashlight. But atoms aren't as amenable as light to being reflected: When an atom hits a surface, it often sticks or bounces off in an unpredictable direction, which dissipates the beam. To get around this problem, the Amsterdam physicists started with a beam of hydrogen atoms cooled to 0.5 K so that they were moving very slowly, and aimed them at a very special mirror: an 18-millimeter hollow hemisphere of highly polished quartz, coated with a film of superfluid helium (helium cooled so much that its individual molecules start moving in unison instead of at random, as they do in most fluids). When the hydrogen atoms hit the superfluid helium, they bounced off—via "quantum reflection." In one test of the mirror, some 80% of the atoms striking it were directed toward its focal point.

Atom optics was "just a collection of demonstrations" until a year or two ago.

—David Pritchard

Like all atom focusing, that's a lot of wizardry for only modest efficiency. Instruments based on atom interferometers rather than lenses may, however, be a little less challenging—and hence a bit closer to practical application. An atom interferometer works on the same principle as an optical interferometer: A single wave is split into two parts, which travel independently for a while and then are recombined, forming an interference pattern, visible on a screen as a regular pattern of bright and dark lines. The bright lines show where the two waves are in phase and reinforce each other; at the dark spots, the two waves are out of phase and cancel each other out.

The value of an interferometer, whether optical or atomic, is that it is extremely sensitive to anything that affects the two beams while they are separated—if something changes one of the beams even slightly, it causes a major and noticeable change in the interference pattern. Light interferometers can record changes in the length of a beam path, for example—and, as Michelson and Morley realized, they could also reveal tiny variations in the speed of light. Replacing the light with atoms should open the way to new kinds of measurements. Since atoms are affected by gravity, atom interferometers should allow quite accurate determinations of local gravitational fields. And physicists already have a list of atomic properties they'd like to measure with atom interferometers, such as the polarizability of atoms or phase shifts caused by collisions with other atoms.

Last May and July, four groups published descriptions of atom interferometers of completely different designs (*Science*, 17 May 1991, p. 921). Pritchard's team, for instance, chose a design modeled on classical optical interferometers. A beam of atoms was split into two by a diffraction grating (a "picket fence" whose 0.2-micron-wide pickets are spaced 0.4 microns apart). The two in-phase beams then traveled independently to a second grating, which bent them back toward each other and created an interference pattern.

Pritchard describes the necessary next step: "We're trying to make an interferometer work with a septum between the two beams so you can, for instance, put a field on one side." In this way, one of the separated atomic beams could be subjected to an electric field or some other force that doesn't influence the second beam, and the resulting interference pattern will offer a measure of that force.

Even before atom lenses or interferometers are perfected, atom-optics proponents are wondering how far they can push the underlying analogy. Perhaps the most ambitious idea they are toying with is an atom analogue of a laser. Lasers emit beams of coherent light—ones in which all the photons have the same wavelength and phase. The first step toward getting a beam of atoms to march in this kind of lockstep, Pritchard surmises, might be to achieve a bose condensation of the atoms—a theoretical state in which many of the atoms are in the same quantum state. No one has ever observed bose condensation, but the theorists believe it should exist given the right conditions. "An atom trap filled with bose-condensed atoms might emit a coherent atom beam if it had a partially transmitting hole at one end," Pritchard says.

Pritchard already has a name picked out. Since "laser" comes from "light amplification by stimulated emission of radiation," he suggests the analogous "atom amplification by stimulated emission of atoms," or "aasea." He doesn't say how you should pronounce it. ■ ROBERT POOL

ADDITIONAL READING

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