

# LASER OPTICS OF NEUTRAL ATOMIC BEAMS

Charged-particle beams are easily manipulated by magnets. Beams of neutral atoms pose a harder problem. A new atomic-beam optics is using fields of laser light to serve as lenses and mirrors.

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In ordinary optics one exploits the interaction of radiation with matter to manipulate beams of light. One can also turn the tables and control beams of charged or neutral material particles through their interaction with light. There are deep analogies and similarities between these two sorts of optics, even though they involve very different kinds of interactions between matter and radiation. Perhaps one can exploit every such interaction for some kind of "optics"—controlling beams of photons or massive particles. In this article we will describe recent developments in the laser optics of atomic beams—how experimenters are using the radiation pressure of laser light to manipulate neutral atoms.

The classical Maxwell theory tells us that light exerts pressure. In his fundamental *Treatise on Electricity and Magnetism* James Clerk Maxwell pointed out that an electromagnetic wave propagating in a medium will exert a pressure in the direction of propagation, at each point equal to its local energy density. Even though the pressure exerted by light from ordinary sources is very small, the effect was experimentally demonstrated at the turn of the century by Piotr Lebedev in Russia and E. F. Nichols and G. F. Hull in the United States. Lebedev also showed the effect of light pressure on gases, and he anticipated the possibility of dramatic pressure increases in conditions of resonance between radiation and atoms or molecules.

The next important step was taken in 1909 by

Einstein. He considered light-pressure fluctuations due to the fact that atoms emit and absorb radiation in light quanta with discrete momenta. In 1933 Otto Frisch in Hamburg demonstrated such discrete momentum transfers from photons to free atoms by observing the deflection of a beam of sodium atoms by the resonant radiation of a sodium-vapor lamp.

## Laser light

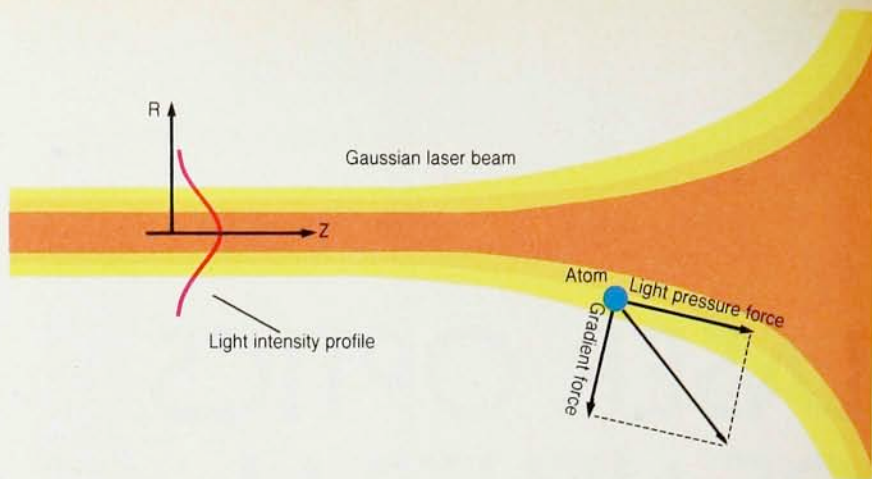
The invention of the laser gave us coherent light sources of high spectral brightness, monochromaticity and directivity. Light pressure, which had been a barely perceptible phenomenon, now became a plausible means of controlling atomic motion, and a variety of explicit suggestions were soon put forward. In 1968 one of us (Letokhov) proposed the use of standing light waves to localize and channel atoms.<sup>1</sup> Two years later Arthur Ashkin at Bell Labs demonstrated the levitation of micron-size particles at the focus of a laser beam.<sup>2</sup> Laser cooling of atoms was proposed in 1975 by Theodor Hänsch and Arthur Schawlow at Stanford. David Wineland and Hans Dehmelt at the University of Washington made a similar suggestion for cooling ions.<sup>4</sup> In 1976 Letokhov and his colleagues at the Institute for Spectroscopy proposed the localization of cooled atoms in a three-dimensional standing light wave.<sup>5</sup>

The experiments were soon under way. In 1978 Ashkin and his coworkers were able to focus a beam of atoms by means of the potential-gradient force of laser light pressure.<sup>6</sup> Over the next several years our group was able to decelerate<sup>7</sup>, monochromatize and cool<sup>8</sup> atomic beams. In 1981 William Phillips and Harold Metcalf at the US National Bureau of Standards were able to cool a beam of sodium atoms down to 0.07 K.<sup>9</sup> In 1985 Steven

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**A Gaussian laser beam**, because its intensity profile is not uniform, exerts a gradient force on the dipole moment that intense light induces in an atom.

Thus the resultant force of the laser beam is not simply in the propagation direction in which the light pressure force acts. **Figure 1**



Chu, Ashkin and colleagues at Bell Labs<sup>10</sup> succeeded in cooling a sodium beam down to  $2.5 \times 10^{-4}$  K, which we thought to be the theoretical minimum temperature achievable by laser cooling. More recently the theorists have had to rethink the issue. Last year Phillips and company<sup>11</sup> cooled a beam of sodium atoms far below the supposed theoretical cooling limit.

Our group achieved resonant collimation of an atomic beam by two-dimensional cooling in 1984.<sup>12</sup> The following year Phillips's group<sup>13</sup> and another NBS group,<sup>14</sup> led by John Hall,<sup>14</sup> were able to bring atomic beams to a full stop. Phillips's group developed a magnetic trap to hold and cool the atoms of the stopped beam. A year later Chu and company accomplished similar trapping and cooling with an optical trap<sup>15</sup> (See *PHYSICS TODAY*, June 1985, page 17, and September 1986, page 17.) Our suggestion that atoms could be localized and channeled by standing waves of laser light was realized experimentally in 1987 by Claude Cohen-Tannoudji and colleagues at the Ecole Normale Supérieure in Paris.<sup>16</sup> Also, a Bell Labs-MIT collaboration developed a hybrid "magneto-optic" trap for atoms.<sup>17</sup>

These experiments have demonstrated that physicists now have at their disposal a new tool powerful enough to encourage the development of a new kind of optics—the optics of neutral atomic beams. This article will discuss a number of recent experiments on the collimation, focusing and mirror reflection of neutral atomic beams. We regard these experiments as beginning steps on the way to the development of optical elements for handling atomic beams.

## Radiation forces on an atom

By radiation force we mean the total force due to the interaction between laser light and an atom. Depending on the wavelength, intensity and spatial-temporal structure of the light field, the radiation force can be an extremely complicated function of the atomic position and

velocity. But things are simplified by the fact that all the studies of light-pressure forces have been done with only three types of light fields: plane waves, Gaussian profile beams and standing waves. We will therefore restrict ourselves to these field configurations. The theory of atomic motion in such fields is quite well developed.<sup>18</sup> We will consider these three cases only qualitatively.

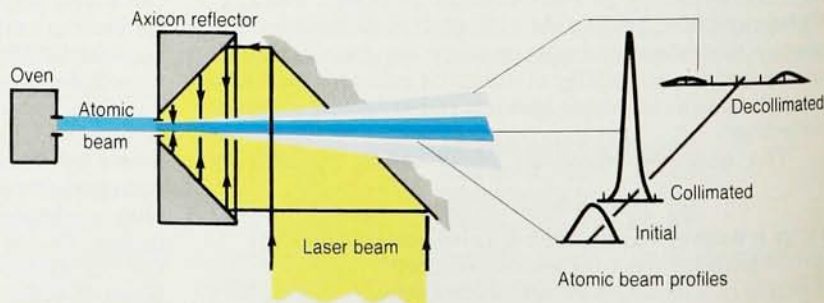
**Plane wave.** Consider a plane wave directed along the  $z$  axis with its frequency tuned to resonance with the absorption frequency of an atom in the wave. The atom absorbs the laser photons directed along the  $z$ -axis and reemits them spontaneously in all directions. As a result, the atom is acted upon in the direction of the wave by a radiation force whose maximum magnitude is given simply by the product of the photon momentum  $\hbar k$  and the maximum photon scattering rate  $\gamma$ , where  $k$  is the wavenumber of the laser light. Suppose the atomic absorption frequency  $\omega_0$  is not exactly in resonance with the laser frequency  $\omega_1$ . Let them differ by a small detuning frequency shift  $\Omega \equiv \omega_0 - \omega_1$ . Suppose further that the atom is not initially at rest; it has velocity projection  $v_z$  in the direction of the light wave. Then the radiation pressure force  $F$  will be given by

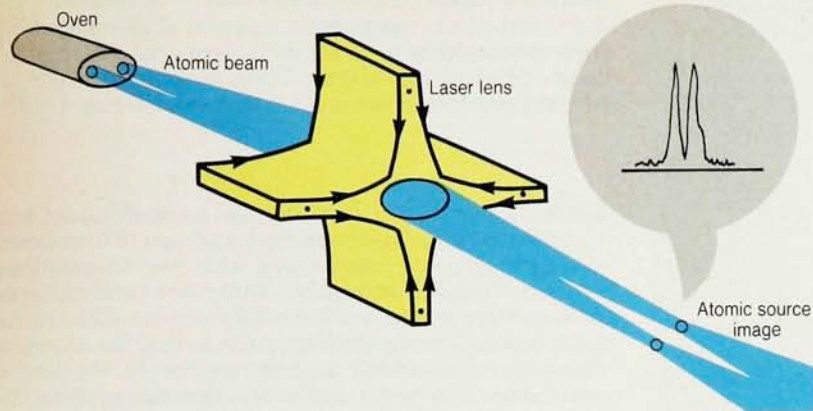
$$F = \hbar k \gamma G / [1 + G + (\Omega - \hbar k v_z)^2 / \gamma^2]$$

where  $G = I/I_s$ ,  $I$  being the light intensity and  $I_s$  the atomic-transition saturation intensity. The acceleration of a sodium atom under such a laser-light force can reach  $10^8$  cm/sec<sup>2</sup>—a hundred thousand times the acceleration of gravity.

**Gaussian laser beam.** An atom placed in a laser beam of finite width is acted upon by an additional gradient force due to the transverse inhomogeneity of the light field, as shown in figure 1. This force can be understood simply from the classical consideration of a dipole in an inhomogeneous field. An atom in a laser field acquires a dipole moment, and the field gradient acts on

**Collimating** an atomic beam by means of laser light. The atomic beam passing through a conical axicon reflector is irradiated from all sides by laser light detuned toward the red from the atomic absorption frequency. The resulting radiation-pressure forces narrow the angular divergence of the atomic beam (see beam profiles). Detuning the laser towards the blue decollimates the atomic beam. **Figure 2**





**Focusing and imaging** an atomic beam with laser light. Four divergent laser beams impinge on the atomic beam, forming a "laser lens." Because the laser wavelength is precisely in resonance with the atomic absorption wavelength, any atom moving away from the axis is pushed back toward the axis so that a point source of atoms is imaged at another point. The beam profile in the image plane shows the double peak that images the two oven slits. **Figure 3**

this dipole moment. Depending on the detuning of the laser frequency from the atomic-transition frequency, the field will either expel the atom out of the beam (if  $\omega_1$  is greater than  $\omega_0$ ) or draw it toward the beam center (if  $\omega_1$  is less than  $\omega_0$ ). The gradient force is given by

$$F_{gr} = \frac{\hbar(\rho/\rho_0^2)(\Omega - kv_z)G}{1 + G + (\Omega - kv_z)^2/\gamma^2}$$

where the laser-beam radius  $\rho_0$  is much larger than  $\rho$ , the distance from the atom to the laser-beam axis.

**Plane standing wave.** A standing wave can be formed by two counterpropagating plane traveling waves. When the radiation intensity is low ( $G$  much less than 1), the force in the standing wave is simply the sum of the forces of the component waves. As the radiation intensity is increased, the modulation of the laser-field intensity at half the wavelength comes into play. This, in turn, causes the gradient force to become manifest. Furthermore, when the radiation intensity is high ( $G$  much greater than 1), the atomic motion is affected by stimulated reemission of photons, which, in the presence of a field inhomogeneity, give rise to a velocity-dependent gradient force component.<sup>19</sup> This force arises when an atom moves in an intense and highly inhomogeneous field whose strength varies significantly during the time it takes the atom to decay spontaneously. It affects atoms moving slowly along the laser-beam axis. Unlike the radiation-pressure force in a traveling wave, this retarding force can grow without limit as one increases the intensity of the laser light.

## Collimating an atomic beam

We now consider how the different forces produced by these laser beams can be exploited to control atomic beams. The need to collimate a beam of particles arises whenever one has to increase their phase-space density—to compress their spatial and velocity distributions. The method of compression will depend on the particular particle species. Common to all these methods is the use of dissipative processes, because Liouville's theorem tells us that conservative forces alone cannot alter phase-space density. Light charged particles, for example, are collimated by radiative friction; protons and antiprotons by electron cooling; and heavy particles by ionization loss.

The dissipative force most effective for neutral atomic particles is the laser radiation pressure. The atomic-beam collimation experiments performed to date have used either the radiation-pressure force<sup>20</sup> or the retarding force.<sup>16</sup> Each of these schemes has its own advantages and disadvantages. The radiation-pressure force lets one obtain atomic beams of narrower angular divergence. The

merit of the retarding force is faster beam collimation, but the ultimate collimation angle achievable by this means is much larger.

Let us consider collimation by the radiation-pressure force in more detail. The atomic beam illustrated in figure 2 is irradiated on all sides by an axisymmetric light field whose frequency  $\omega_1$  is shifted toward the red relative to the atomic transition frequency  $\omega_0$ . The axisymmetric field is formed by reflecting a laser beam off the inner surface of a conical "axicon" reflecting surface. In the plane of the figure, this field consists of two counterpropagating light waves whose intensities are equal at any point within the axicon.

If  $\omega_0$  exceeds  $\omega_1$ , an atom moving with radial velocity  $v_\rho$  in the axisymmetric light field is acted upon by a radiation-pressure force directed *against*  $v_\rho$ . Because of the Doppler shift, an atom absorbs more effectively those photons that come from the light propagating counter to its velocity vector. Therefore the total force of the laser light converging on the atomic beam produces a rapid narrowing of the transverse velocity distribution in the inner region of the axicon. Thus one gets the desired reduction of the angular divergence of the beam.

The joint effect of radiative friction and momentum diffusion establishes a stationary atomic velocity distribution that determines the ultimate collimation angle

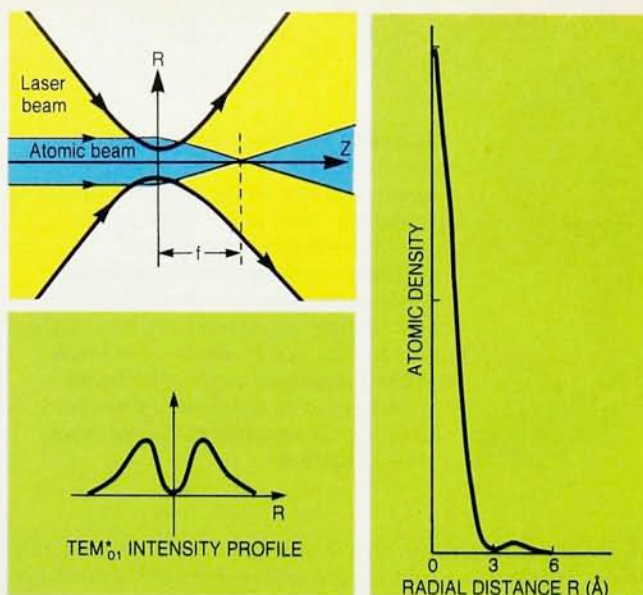
$$\Delta\phi_{\min} = (1/v_z)(\hbar\gamma/M)^{1/2}$$

where  $M$  is the atomic mass and  $v_z$  is the atomic velocity along the atomic-beam axis. For a thermal atomic beam, the ultimate collimation angle is on the order of  $10^{-3}$  or  $10^{-4}$  radians. If the initial beam divergence was 0.1 radian, the on-axis atomic-beam intensity can be increased perhaps a millionfold.

We did the experiment with a beam of sodium atoms. Figure 2 shows the beam profiles before and after interaction with the laser field. The collimation process is very sensitive to the precise laser frequency. To effect collimation, we detuned the laser light toward the red by 13 MHz. The longitudinal atomic velocity  $v_z$  was  $7.3 \times 10^4$  cm/sec. The before and after beam profiles show a fivefold increase in the on-axis atomic-beam intensity and a considerable narrowing (collimation) of the beam. Changing over to positive detunings caused a broadening (decollimation) of the beam. The on-axis beam intensity in this latter case was observed to decrease by more than three orders of magnitude.

## Focusing and imaging

The principal element in any sort of optics is a lens. It is



**Atomic objective lens** is expected to focus atomic beams down to a width of a few angstroms, as shown in the calculated atomic-beam profile (rightmost graph). The atomic beam is focused by being passed through a focused laser beam. The laser field is in the  $TEM_{01}$  mode, whose radial intensity profile is shown at the bottom left. **Figure 4**

optics. Figure 3, which shows the more elaborate four-laser-beam lens, illustrates the imaging of a "two-point" atomic source—an atomic oven with two 0.5-mm-diameter holes spaced 2 mm apart. Without the laser lens, the atomic beam profile is a wide, diffuse spot. With the two laser beams forming the lens in the path of the atoms, we found that the atomic trajectories obeyed the laws of neutral-particle beam optics. In the image plane, the beam profile consisted of two well-defined peaks, each corresponding to one of the atomic source holes.

A serious drawback of this laser lens is its insufficient resolution: The minimum focal spot diameter is about  $50\text{ }\mu\text{m}$ . As was the case in the old Bell Labs focusing experiment, the resolution limit is due to momentum diffusion, which smears the trajectories of the atoms interacting with the laser lens field.

Resolution can be materially improved by resorting to the old idea of the gradient force, but now with a different laser field configuration and a different atom-field interaction geometry. We have proposed<sup>22</sup> an "atomic objective lens" with a resolution of a few angstroms. Such an objective lens, illustrated in figure 4, is essentially a focused laser field with its frequency tuned well away from the atomic-transition frequency. The focused laser field is in the  $TEM_{01}$  mode, whose radial intensity profile is shown in the figure. The atomic beam propagates along the lens axis. The tight focusing of the laser radiation yields an effectively "thin" lens, and the choice of the  $TEM_{01}$  mode and the large frequency detuning allow us to achieve a good approximation to an "ideal" objective lens. The 1978 Bell Labs paper<sup>6</sup> had pointed out the merits of the  $TEM_{01}$  mode.

To determine the maximum resolution of such an atomic objective lens one treats the atomic beam as a superposition of plane de Broglie waves, and the laser field through which it propagates is taken to be a transparent medium whose phase transmission function depends on the distance from the lens axis. These plane waves acquire phase advances in the laser field that lead to their subsequent focusing in the focal plane of the atomic objective lens. The minimum focal-spot diameter is determined mostly by the diffraction of the de Broglie waves by the lens aperture. Additional limitations are due to spherical and chromatic aberrations and diffusion aberration associated with the atomic momentum diffusion in the laser field. Nevertheless, the calculations show that one can choose laser-field and atomic-beam parameters such that the resolution of the lens will come very close to its diffraction limit. For instance, if the transverse dimension of the lens is taken to be equal to a few wavelengths and the laser power is about 1 W, the focal spot diameter of the atomic beam, as shown in figure 4, should not be much greater than a few angstroms.

## Atomic-beam reflection

Mirrors are no less important than lenses. A mirror can be used both for focusing and reflecting. Focusing by means of a concave mirror has certain advantages over lens focusing: It avoids chromatic aberration. This is particularly important for particle-beam optics, where chromatic aberration can be especially severe.

The atomic mirror idea was first suggested<sup>23</sup> by

therefore essential to create laser field configurations capable of focusing neutral atomic beams. There are at present two possibilities for focusing an atomic beam: the gradient force and the pressure force of spontaneous radiation.

The focusing of an atomic beam by means of the gradient force was first demonstrated ten years ago at Bell Labs.<sup>6</sup> In their scheme, the atomic beam propagated along and inside a narrow laser beam. The laser frequency was tuned below the atomic-transition frequency, so that the gradient force was directed toward the laser-beam axis. In this way the width of the atomic beam was compressed down to a minimum of  $26\text{ }\mu\text{m}$ .

Our 1986 experiment<sup>21</sup> used a different laser field configuration, similar to that illustrated in figure 3. In the general case, our method uses four divergent Gaussian laser beams propagating toward a point on the atomic beam. The narrow waists of the four laser beams are equidistant from this central point of the configuration. The laser frequencies are tuned to precise resonance with the atomic absorption frequency. Under such conditions, an atom moving away from the atomic-beam axis is acted upon by a spontaneous radiation-pressure force that tends to bring it back to the beam axis.

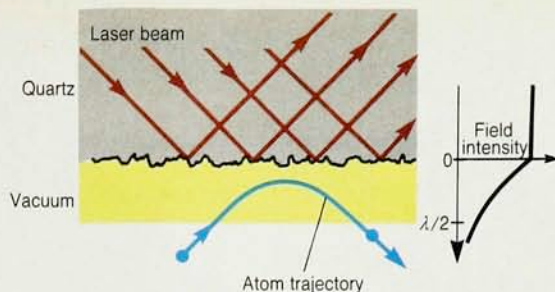
The effect of the gradient force in this case is insignificant. Such a configuration is, in effect, a "laser lens" for a beam of neutral atoms, because it can be shown that an atomic beam issuing from a point (the analog of a point source in light optics) is focused onto another point after interacting with the laser. Furthermore, one may define a focal length  $f$  for such a lens in terms of the geometric, optical and atomic parameters of the system, and derive the laser lens formula

$$1/S + 1/L = (1/f)(1 - d/2L)$$

where  $d$  is the thickness of the laser, and  $S$  and  $L$  are, respectively, the atomic-source and image distances from the lens. The laser lens is quite localized in space. Its characteristic size  $d$  along the atomic beam is much less than  $S$  and  $L$ . Under these conditions, the lens formula looks just like the usual optical lens formula.

Our first successful focusing experiment was conducted with a beam of sodium atoms and a laser lens formed by only two counterpropagating Gaussian beams. Such a laser lens is analogous to a cylindrical lens in light

**Atomic mirror.** A laser beam totally reflected at the inner surface of a quartz plate forms a very thin "evanescent" surface light wave just outside the plate. The enormous intensity gradient of this surface wave produces a gradient force strong enough to turn around the trajectories of approaching atoms. **Figure 5**



Richard J. Cook and Richard K. Hill at the US Air Force Institute of Technology in 1982. Figure 6 illustrates such an atomic mirror. It is formed by a very thin "evanescent" (surface) wave produced by total internal reflection of a laser beam at a dielectric-vacuum interface. The thickness of this surface wave is on the order of the wavelength. The laser radiation intensity on the surface of the dielectric equals the intensity of the initial laser wave inside the dielectric, but in the vacuum it drops almost to zero very abruptly—within a few wavelengths of the surface.

In such a surface wave one has an enormous light intensity gradient—the largest gradient seen anywhere in optics. An atom placed in a such a surface wave of laser frequency higher than the atomic-transition frequency experiences a gradient force tending to expel it from the wave and into the vacuum. If the atom approaches the surface wave from the vacuum side, it slows abruptly to zero normal velocity in the surface wave, then accelerates in the wave in the reverse direction away from the surface. If its transverse velocity (normal to the surface) does not exceed some critical maximum, the atom's angle of incidence will approximately equal its angle of reflection—much like light striking an ordinary mirror.

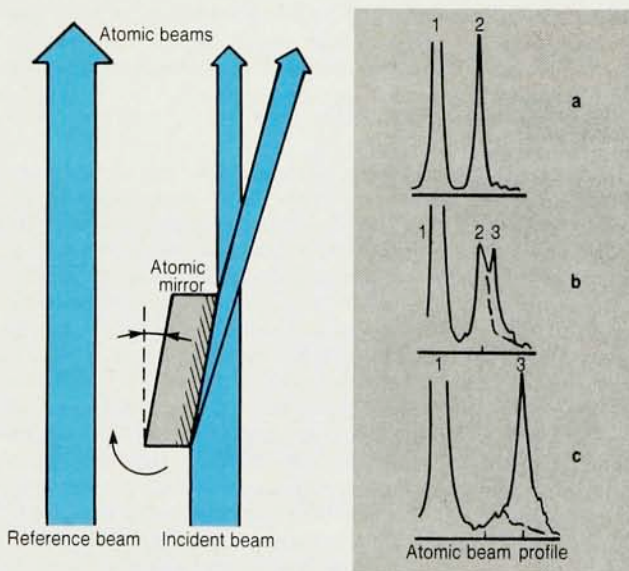
The maximum transverse atomic velocity corresponds to a kinetic energy equal to the barrier height of the surface wave. If the transverse atomic velocity is higher than this critical maximum, the atom will reach the dielectric surface and reflect from it in a diffuse manner. For typical cw laser radiation with a power of 1 watt and, for example, a sodium atom with a thermal velocity of  $6 \times 10^4$  cm/sec, the critical transverse velocity will be  $5 \times 10^2$  cm/sec. In that case the angle of incidence must be within  $10^{-2}$  radian of the surface. With laser-cooled atomic beams or pulsed dye-laser radiation, there is no limitation on the angle of incidence; reflection is possible even if the atomic beam is normal to the atomic mirror.

Our group reported<sup>24</sup> the first observation reflection by an atomic mirror in 1987. We used a beam of sodium atoms. The atomic mirror was a plane-parallel plate of fused quartz with a beveled lateral face through which we passed laser radiation. To increase the surface area of the atomic mirror, we made use of repeated total internal reflection of the laser beam. Figure 6 shows the arrangement of the incident and reflected atomic beams, as well as a reference beam. The figure also shows profiles of these three beams. When the atomic mirror is parallel to the atomic-beam axis so that the atoms fly past it, the profile shows only the reference and incident beams. If the mirror is tilted so that it cuts off the atomic beam, the latter is observed to be reflected. As one increases the tilt angle of the mirror still further, the angle of reflection increases as well, but the number of atoms undergoing mirror reflection decreases because some atoms reach the mirror surface and suffer diffuse reflection. The maximum angle of reflection observed in the experiment was about  $0.4^\circ$ . The mirror reflectivity was close to 100%.

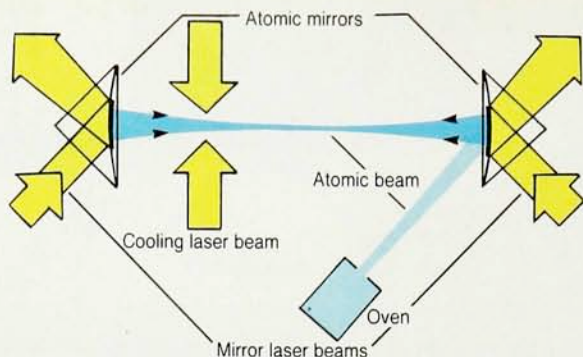
Another remarkable property of the atomic mirror is its ability to reflect atoms in a quantum-state-selective fashion. This selectivity arises from the dispersive character of the relationship between the gradient force acting

on the atoms and the laser radiation frequency: When the detuning of the laser frequency with respect to the atomic absorption frequency is positive, the gradient force drives the atoms away from the surface. When it is negative, the force draws the atoms to the surface, whereupon they undergo diffuse scattering. Suppose that a beam of atoms distributed among several sublevels of the ground state impinges on the atomic mirror. The atoms in a sublevel for which the transition frequency to an excited state is lower than the laser frequency will be reflected at the mirror, whereas the rest will scatter in a diffuse manner. The reflected beam will thus contain only particles in a single energy level. Last year we observed selective reflection of atoms at two hyperfine splitting sublevels of the ground state in sodium. We found that the mirror reflectivity for atoms in the  $F=2$  sublevel was at least 100 times greater than for the  $F=1$  sublevel.

Note that such selective reflection can also be expected for molecules. This opens up the possibility of production and spectroscopy of molecular beams in a single vibrational-rotational energy level.



**Reflecting atomic beams.** An atomic mirror like that in figure 5 was used in our laboratory to reflect an atomic beam. The quartz mirror can be tilted in and out of the atomic beam. When the mirror does not impinge on the beam (a), the beam profile (right) shows peaks for the undisturbed beam (2) and a reference beam (1). Tilting the mirror partially into the beam (b) produces a third peak (3) for the reflected beam. When the mirror is tilted further (c), cutting off the entire beam, the angle of reflection is increased. **Figure 6**



**Atomic-mirror cavity.** An atomic beam is injected into a cavity formed by two concave atomic mirrors. The cavity collimates the beam and narrows its velocity distribution. While in the cavity, the atomic beam can also be cooled by additional lasers. **Figure 7**

It is also possible to create spherical atomic mirrors and cavities. Figure 7 shows one possible atomic-cavity configuration. It is essentially an optical cavity with the physical mirrors replaced by light-induced mirrors. One might inject atoms into such a cavity by the laser collimation of an external atomic beam. The maximum steady-state density of atoms in the cavity would be determined by the rate of their injection into the cavity and their lifetime therein. One of the parameters that characterize the light field in an ordinary optical cavity is its degeneracy—the number of photons per cavity mode. For laser radiation, the degeneracy is fairly high. Our estimates show that the realization of a pseudo-optical cavity for atomic de Broglie waves would, in principle, allow a high degeneracy to be achieved at a relatively low atomic density. This would result from the velocity monochromatization and collimation of the atomic waves in the cavity.

## Prospects

After only these first few experiments we can already say that experimenters have come into possession of an entirely new method for controlling atomic beams. As laser technology advances, it will become possible not only to perfect the elements of neutral atomic-beam optics, but also to pass on to molecular beams. Some possible applications of neutral atomic-beam optics are already clear. Collimation of atomic beams lets one shape them and improve their divergence and phase density—all this in an isotope-selective fashion. Beyond increasing atomic-beam density, atomic-beam focusing can help create an atomic microscope. It is not difficult to envisage a scanning transmission microscope or a reflection microscope of this sort. The scattered or reflected atoms could be registered by existing single-atom detection techniques.

Atomic mirrors could be used as high-speed deflectors, modulators and shutters for neutral atomic beams. They could also be used to create traps for ultracold atoms. Concave atomic mirrors could serve as optical elements in an atomic microscope because they can focus atomic beams onto a spot with a diameter comparable to the de Broglie wavelength, the atom-laser interaction time being too short for momentum diffusion to become a limiting factor. Sharply focused atomic beams with focal-spot diameters of a few angstroms would let one observe atomic collisions and study atomic scattering under strictly controlled conditions. It would be interesting to extend this technique to molecular beams. This would yield better insight into molecular interaction dynamics.

In the restricted scope of this article we have not discussed several other analogs of conventional optical elements, nor have we covered interference phenomena. One can, for example, use configurations of laser light to serve as diffraction gratings and beam splitters for atomic beams. Much impressive work in these areas has been done in various laboratories around the world.

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