Sodium Atoms Stopped and Confined

Particles in a fast-moving atomic beam can be stopped in their tracks by laser light and subsequently confined in space for a second or so

For spectroscopists, the ideal sample would be a collection of atoms or molecules sitting motionless in space for a long period of time. This ideal may never be achieved, but the next best thing is on the way. Two groups have confined by quite different means very slowly moving sodium atoms in small volumes, from which the particles gradually leak out with time constants of 0.1 to 1 second.

At the National Bureau of Standards (NBS), Gaithersburg, Maryland, Alan Migdall, John Prodan (now at Lockheed Missiles and Space Company, Sunnyvale, California), and William Phillips collaborated with Thomas Bergeman and Harold Metcalf of the State University of New York at Stony Brook to demonstrate for the first time that slow-moving neutral atoms could be trapped by means of a magnetic field that creates an energy well for the atoms (*1*).

This group collected about 10^5 sodium atoms in a trap volume of 20 cubic centimeters (cm^3). The number of trapped atoms, which had velocities ranging from 0 to 3.5 meters per second (m/sec), decayed with a time constant of 0.83 second because of collisions with background atoms in the imperfect vacuum. The theoretical trapping time in a perfect vacuum is greater than 1000 seconds.

Meanwhile, at AT&T Bell Laboratories, Holmdel, New Jersey, Steven Chu, Leo Hollberg, John Bjorkholm, Alex Cable, and Arthur Ashkin created what they call "optical molasses" from the photon field generated by three pairs of laser beams propagating in opposite directions along three mutually orthogonal axes (*2*). Because there is no energy well, the atoms in the molasses were not, strictly speaking, trapped, but it took them a considerable time to diffuse out.

As at NBS, the Bell Labs group confined sodium atoms, but they achieved a higher density with about 2×10^5 atoms of average velocity 0.6 m/sec in a smaller volume of 0.2 cubic centimeter. The confinement time was also less than in the NBS experiment with a time constant of 0.1 second. However, since the time to diffuse out of the trap scales with the square of the trap size, the time could be increased by enlarging the confinement volume.

Numerous other groups in the United States and Europe are also in or getting into the trapped atom game and thereby complementing the players in the more mature field of ion trapping. The interest follows from the ruinous effect atomic motion has on high-resolution spectroscopy. Usually, the main offender is the Doppler effect in which the position of a spectral line is shifted by an amount proportional to the ratio of the atom velocity to the velocity of light. With a distribution of atomic velocities, the spectroscopist measures a much broadened spectral line shape.

Although researchers have devised several means of dealing with this so-called first-order or linear Doppler effect, there is also a second-order Doppler effect that is proportional to the square of this ratio. Though the spectral line broadening is smaller than that due to the linear Doppler effect since the ratio is always less than 1, it cannot be remedied other than by slowing the atoms down. Moreover, there is a further broadening due to the finite interaction time between the light beam and the atoms. The broadening is inversely proportional to the time the atoms "see" the light and can be a problem in experiments in which an atomic beam and the light beam are made orthogonal to avoid the linear Doppler effect.

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The spectral line broadening due to the second-order Doppler effect and the finite interaction time are so small (a few thousand hertz for optical frequency light in atomic beams) that for most purposes they are negligible. But laser technology is so advanced in some laboratories nowadays that it is possible to measure spectral lines that are much narrower, and researchers would like to take advantage of this capability. Moreover, substantially improved atomic clocks and frequency standards require the ability to measure narrower lines than this accurately and reproducibly. And some tests of fundamental physical theories, such as relativity, likewise depend on very accurate frequency standards. Spectroscopy and time-keeping are far from the whole story. Physicists are also interested in the properties of very slowly moving atoms. It would be possible to look at collisions between atoms or atoms and surfaces in detail, for example.

Confining atoms is a two-step process. The first step is slowing the atoms down sufficiently that they can be collected, while the collection itself is the second part. Earlier this year, two American groups reported that they could stop or even reverse the motion of atoms in an atomic beam by shining a laser head on into the beam. Once again, the researchers used sodium, which is so often the subject of such experiments because it is convenient to work with. But the principles are quite general.

Atomic beams come from a heated source of several hundred degrees Kelvin (K) that emits atoms with an average or thermal velocity of several hundred meters per second. The high temperature also gives rise to a distribution of velocities around this value whose width is a measure of the "temperature" of the beam. A narrower distribution means a lower temperature, so the researchers frequently use the term laser cooling. Absorption and reradiation of the laser light can both slow down the atoms in the beam and cool them. Although the two effects go together, a given technique may be more effective at one than the other.

The basic force for slowing and cooling atoms is called radiation pressure. Absorption of a photon from the laser beam imparts a momentum to the atom in the direction opposite to that of its motion, which is what causes the slowing. Between absorptions, the atom spontaneously reradiates a photon as fluorescence when it relaxes back to its lower energy quantum state. Emission of a photon also gives the atom a kick, but the photons randomly fly off in a symmetric pattern, so that the net momentum change due to emission of a large number of photons averages to zero (*3*).

One major difficulty with this conceptually simple scheme derives from the linear Doppler effect. As an atom in the beam gradually slows down, the frequency of the light it will absorb (its apparent resonant frequency) slowly increases, whereas the laser frequency is normally fixed. It takes about 30,000 photons of yellow light to completely halt a sodium atom of initial velocity 1000 m/sec. But after the absorption of only about 100 photons, the resonant frequency is shifted enough that it no longer matches that of the laser, and further absorption stops.

In principle, the most obvious method of dealing with this Doppler shift is to scan the laser frequency in synchronism with the slowing of the atoms and thereby maintain the resonance. However, another way is to find a way to keep the resonant frequency constant despite the slowing. At NBS, Prodan, Migdall, and Phillips teamed with Ivan So and Metcalf of Stony Brook and with Jean Dalibard of the Ecole Normale Supérieure in Paris to take the latter approach by making use of the Zeeman effect (*4*).

In a magnetic field, the energy of an atom in a particular quantum state depends on the strength of the field. Hence the resonant frequency, which depends on the energies of the quantum states the atom is in before and after the absorption of a photon, also is dependent on the field strength. By varying the strength of the field along the length of the atomic beam in such a way that the resonant frequency decreases by an amount that exactly compensates for the increase due to the Doppler effect, it is possible to keep the frequency fixed.

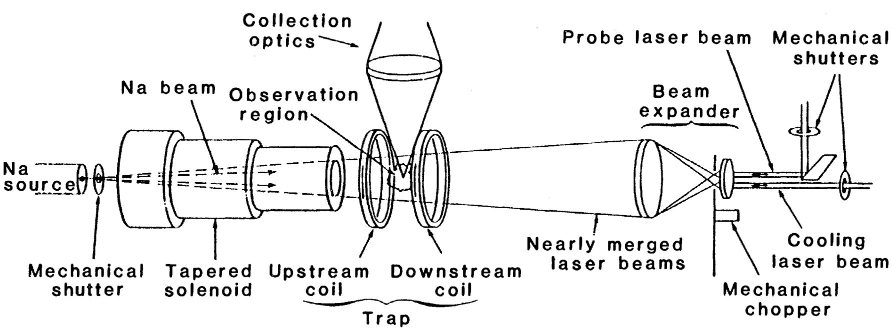
Earlier work by Prodan, Phillips, and Metcalf had demonstrated that sodium atoms could be both slowed and cooled by this means. The researchers had measured velocity distributions centered around 40 m/sec with an effective temperature of 0.07 K for a sample of atoms from a beam of initial thermal velocity 1000 m/sec and temperature 950 K. In the more recent work, the expanded collaboration brought samples of sodium atoms of density 10^6 per cubic centimeter to rest. Actually, not every atom was motionless. The effective temperature of the sample was about 0.1 K, corresponding to a width in the velocity distribution, which was centered around 0 m/sec, of 15 m/sec.

The conceptually more straightforward technique of compensating for the Doppler effect by scanning the laser frequency turns out to be technologically more difficult. However, at the Joint Institute for Laboratory Astrophysics (JILA, which is run by the University of Colorado and the National Bureau of Standards, Boulder), Wolfgang Ertmer from the University of Bonn, West Germany, Rainer Blatt (now at the Free University, West Berlin), John Hall, and Miao Zhu have succeeded in stopping samples of sodium atoms by this means (*5*). From an initial thermal velocity of 620 m/sec and temperature of 525 K, the investigators obtained a sample of density 10^6 per cubic centimeter and effective temperature 0.05 K.

Part of the difficulty with scanning the laser frequency is that it is actually necessary to scan two frequencies simultaneously to avoid an effect called, in the jargon, optical pumping. Because of the interaction between the magnetic moment of the sodium nucleus and the moment due to electron spin, the lowest energy quantum state of sodium is split into two states of slightly different energy (hyperfine splitting). While absorption of photons from the laser excites sodium in only one of these, afterward the sodium can decay to either one. After a short time, all the atoms are in the wrong quantum state, and once again absorption ceases.

The NBS, Gaithersburg, group solved this difficulty by using circularly polarized light in combination with the magnetic field already needed to compensate for the Doppler effect. The field itself splits the quantum states involved into a larger number by way of the Zeeman effect. With the correct choice of the initial and final quantum states and with circularly polarized light, quantum mechanical selection rules restrict the excited sodium atom to decay only to the quantum state it originated from, thereby avoiding the optical pumping effect.

National Bureau of Standards



NBS laser cooling apparatus and trap

Sodium atoms emerge from the source at left, are first cooled in the tapered solenoid, and are then stopped and trapped between the two coils about 40 centimeters from the end of the solenoid. The cooling and probe laser run in the opposite direction from the right.

Use of two laser frequencies avoids the need for an applied magnetic field. For example, one frequency can be tuned to excite sodium atoms from each of the two low-energy quantum states arising from the hyperfine splitting. The technological difficulty is getting them to scan synchronously to compensate for the Doppler effect as the atoms slow down. It would be very difficult to get two separate lasers to be so well behaved, for example. The approach taken by the JILA collaboration was to use devices called electrooptic phase modulators. Most of the light of a given frequency that passes through this type of electrooptic modulator is split into several frequencies called side bands that lie symmetrically on each side of the original frequency.

In this case, the largest fraction of the light is in the first side bands. The difference between the frequencies of the light in the side bands and the original light can be controlled by the frequency of the voltage that must be applied to the modulator to make it work, whereas the intensity in the side bands depends on the magnitude of the voltage. To compensate for the Doppler effect during cooling, the investigators used the first side band on the high frequency side of the original laser frequency. As the atoms are cooled and the Doppler effect increases their resonant frequency, the frequency of the voltage on the modulator is increased in such a way that the frequency of the side band increases to match the Doppler shift.

To overcome optical pumping, the group resorted to a second electrooptic phase modulator to generate a second laser frequency. All the laser frequencies exiting from the first modulator pass through the second, which is operated at a fixed frequency of magnitude sufficient to generate additional side bands shifted in frequency enough to match the hyperfine splitting. In this way, all the light derives from the same laser and is swept in frequency at the same time by the first modulator.

To trap atoms cooled by either of these methods in a magnetic field, a field configuration such that the energy of the atom is a minimum in the center of the trap is necessary. Moreover, cooling is necessary before trapping because the energy of the interaction between a neutral atom and a magnetic field is weak compared to the kinetic energy of all but very slowly moving atoms. Trapping ions is comparatively easier because of the large interaction energy between the ionic charge and electric or magnetic fields. In fact, ions are usually trapped, then cooled.

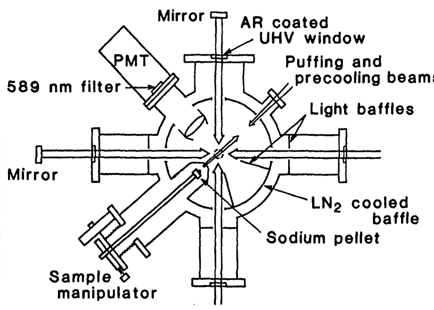
Borrowing from an idea of Wolfgang Paul of the University of Bonn, who made magnetic traps for neutrons, the NBS investigators chose a trap comprising two coils in which the current flowed in opposite directions. At some point on the axis between the coils, which are arranged like the wheels on a chariot, the magnetic field strength is zero, while it increases in every direction away from the minimum. Since the interaction energy is equal to the product of the parallel components of the atomic magnetic moment and magnetic field vectors, however, this field configuration does not in itself guarantee that there is an energy well. With randomly oriented atoms, there would be both positive (confining) and negative (repelling) energy wells with a distribution of depths.

The laser cooling method used by the NBS collaboration turns out to be crucial to solving the trapping problem because all the sodium atoms end up in the same quantum state. According to the Zeeman effect, in a magnetic field, a given quantum state has a specific orientation relative to the field. The end effect is the desired energy well in a volume defined by the coil separation (2.5 centimeters) and inner radius (4 centimeters). The well, which has cylindrical but not spherical symmetry, can confine atoms moving at 3.5 m/sec or less. The use of superconducting coils to produce a stronger field than the 0.025 tesla of the copper coils is a future option for a stronger trap.

The atoms in the trap can be observed by the fluorescence they emit after absorbing light from a probe laser. From the fluorescence intensity and its decrease with time, the researchers estimated the concentration of trapped atoms and the trapping time. While collisions with background atoms provide the present limit on trapping time, the ultimate limit comes from the rate at which the atoms change quantum states. When they enter a state in which the orientation of the magnetic moment reverses, trapping ceases.

Laser physicists have speculated for several years that it should be possible to trap slowly moving atoms in laser beams. Much of the early work concentrated not on radiation pressure but on a second force that is due to stimulated (as opposed to spontaneous) optical processes that exist when there is a spatial gradient in light intensity. Although the effects of this gradient force are observable, a stable trap based on it is difficult to realize. Laser traps could also make use of the radiation pressure. While it has been proved that a stable trap is not possible if only static (cw) beams are used, last year Arthur Ashkin of Bell Labs argued that a stable radiation-pressure trap is possible with dynamic focused laser beams.

Ashkin's idea begins with two counterpropagating laser beams of the same frequency. One laser is focused on a point a short distance before the center of the trap, while the other is focused an equal distance on the other side of the trap center. With this geometry an atom trying to leave the trap center along the axis will feel a force pushing it back into the center due to the difference in the radiation pressure of the two opposing beams. However, atoms moving radially tend to be expelled. To confine atoms radially, one could use the same two laser beams, but exchange the points on which they are focused; that is, each laser focuses on the point on the far side of the trap center. It turns out that this configuration prevents atoms from moving radially away from the trap center but not atom motion along the axis.



AT&T Bell Laboratories

Optical molasses

Sodium atoms vaporized by the puffing laser squirt into the vacuum chamber, where they are first precooled and then confined by six intersecting laser beams. The circle in the center represents the two vertical beams.

To achieve a net confinement in all directions, Ashkin proposed periodically reversing the two configurations at a rate of several kilohertz. The situation is quite akin to the so-called Paul trap, which uses radio-frequency electric fields to confine ions to small oscillatory radial and axial motions in the trap. Although the method has not been demonstrated for atoms, Ashkin and Joseph Dziedzic recently showed that it works for micrometer-sized dielectric spheres (*6*).

While it also requires the use of counterpropagating laser beams, optical molasses works by a mechanism different from a trap. First of all, there are six beams, one pair for each of three mutually orthogonal axes. Second, the beams are not focused. And, finally, the beams are static and do not change intensity or direction. Without the dynamical focusing, there is no trapping effect. Instead, there is a three-dimensional cooling effect, rather than the one-dimensional effect when atomic beams are slowed. In short, whatever direction the atoms move away from the center, there is a force opposing them. The result is that the atoms randomly walk in a viscous fluid of photons and only slowly diffuse away. Since the viscosity is so large, the storage times can be comparable to those demonstrated by the NBS group.

There are two effects at work in the optical molasses. The three pairs of lasers quickly and effectively cool the atoms to a very low effective temperature. The temperature is not arbitrarily small, however, because of heating due to the random absorption and emission of photons. Heating also occurs in laser cooling of atomic beams, but the most pronounced result usually is in the directions transverse to the atomic beam, where there is no cooling, so that velocities slowly increase in this direction and the beam diameter gradually blows up. In the molasses, where heating and cooling take place in all directions, the two effects reach a balance, which is what determines the minimum attainable temperature. In the Bell Labs experiments, this temperature was 0.00024 K.

As with magnetic trapping, it is necessary to precool the atomic beam before encumbering it in the molasses. The Bell Labs group used a technique somewhat similar to that at JILA in that they relied on an electrooptic modulator to scan the cooling laser frequency and thereby maintain resonance as the atoms slowed. However, unlike the JILA collaboration, they used separate lasers to generate the two frequencies needed to avoid the optical pumping effect. Atoms with initial velocities of 200 m/sec or less were slowed to about 20 m/sec and allowed to drift into the region where the six laser beams intersected and the final cooling took place.—**Arthur L. Robinson**

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