resolution could be improved quite dramatically by the addition of an antenna in space. Essentially, the antenna's orbital velocity would allow it to sample different regions of the incoming signal very quickly. (In more technical terms, the antenna's signal would rapidly fill in the Fourier transform of the image of the source. The more complete the transform, the sharper the final image.) This would also allow the VLBI network to monitor the very rapid changes going on in objects such as SS433, and would allow it to expand coverage into the Southern Hemisphere.

How do you get such antennas into space? Burke asked. One attractive opportunity offers itself: both NASA and the Pentagon are interested in demonstrating their ability to deploy large antennas in orbit, and in fact there is talk of trying it later in the decade with a 50-meter dish unfolded from the shuttle payload bay. Even if such an antenna stayed up for only a week, said Burke, it could do useful astronomy. Later, depending on NASA's prosperity and its generosity toward astrophysics, a permanent version could be placed on a space platform.

Finally, at the high-energy end of the spectrum, there is the Field Committee's number one priority for astronomy in the 1980's: AXAF, the Advanced X-ray Astronomy Facility. George W. Clark of the Massachusetts Institute of Technology was at Danbury to tell the story.

Since high-energy photons are strongly absorbed in the atmosphere, he explained, x-ray astronomy is totally dependent on space. Yet, in less than 20 years the field evolved from its first sounding rocket flight to the image forming x-ray telescope on the Einstein Observatory.

"Einstein whetted people's appetite," said Clark. In its 2 years of operation between 1979 and 1980, it obtained spectra and detailed images of thousands of objects, both in this galaxy and elsewhere. "Hundreds of astronomers participated," he said. "In effect, Einstein became a national observatory for x-ray astronomers."

"We now know that million-degree plasmas are the most common sources of x-rays, and that these plasmas are found in objects of every kind," he said. Examples include stellar coronas, pulsars, bursters, supernova remnants. "There are millions of sources, some of which emit most of their energy as x-rays."

The next generation x-ray observatory, AXAF, would be a scaled-up version of Einstein capable of ten times better resolution and 100 times the sensitivity for faint objects, said Clark. Like Space Telescope, it would be launched, serviced, and refurbished by the space shuttle, and would operate as a national observatory for at least 10 years.

Unfortunately, he added, the financially strapped NASA has put off a new start on AXAF again and again. And since the demise of Einstein there are no new data coming in. "X-ray astronomy is dying in the United States for lack of facilities," he said. The only missions now funded are foreign—the European EXOSAT and the German ROSAT, for example—and those are not as advanced as AXAF.

Clark serves in a NASA working group seeking ways to trim the price tag on AXAF to under $500 million. But he is not optimistic.

"There is a question whether NASA's growing drive for a space station [*Science*, 10 September, p. 1018] will crowd out space science already battered by the shuttle," he concluded, voicing a fear common in the space science community.—**M. MITCHELL WALDROP**

Laser Light "Cools" Sodium Atoms to 0.07 K

Slow-moving atoms could lead to ultrasensitive laser spectroscopy, atomic timekeeping, and tests of fundamental physical theories

Researchers at the National Bureau of Standards (NBS) in Gaithersburg, Maryland, have "cooled" a beam of sodium atoms emitted from a hot oven to an effective temperature of 0.07 K by irradiating the beam head-on with a laser beam. By absorbing and reradiating about 30,000 photons, each atom is slowed to a speed of about 40 meters per second (m/sec) during the cooling process. The availability of such slow-moving particles could open the way for investigators to make ultrahigh resolution laser spectroscopic studies of atoms and possibly molecules, to create atomic clocks and frequency standards of unprecedentedly high accuracy, and to carry out supersensitive tests of fundamental physical theories, such as quantum electrodynamics and general relativity.

The fundamental problem for spectroscopists who wish to make high-resolution measurements of atoms or molecules in the gas phase is the motion of the particles. The familiar Doppler effect, for example, gives rise to frequency shifts that broaden an intrinsically narrow line in an absorption spectrum. Each particle sees the frequency of the light altered by an amount proportional to its velocity relative to the light source ($\Delta\nu/\nu = \pm v/c$, where ν is the frequency, v is the particle speed, and c is the speed of light). The shift is positive (blue shift to higher frequencies) if the particle moves toward the light source and is negative (red shift to lower frequencies) if the particle moves away from the source. A gas with a thermal distribution of velocities thus exhibits an absorption spectrum that is the superposition of these frequency-shifted absorption lines.

In the 1970's, spectroscopists devised several techniques for dealing with the Doppler effect [saturation spectroscopy, two-photon absorption, crossed atomic beam and laser beam, and variations of these (*Science*, 13 October 1978, p. 141, and 2 July 1982, p. 9)]. But atomic and molecular motion remains a problem for the ultrahigh resolution spectroscopy that the newest laser technology makes possible. The ultimate limitation is the second-order Doppler effect that is due to the dilation of time in special relativity. The frequency shift, being proportional to the square of the particle velocity ($\Delta\nu/\nu = -v^2/2c^2$), is much smaller than that due to the first-order Doppler effect and is always negative (red shift). A second difficulty stems from the finite time the particles spend in the laser beam because the frequency of a light wave that is not infinitely long is uncertain. The uncertainty is inversely proportional to the time the particle "sees" the light ($\Delta\nu = 1/2\pi\Delta t$). Consider a typical atomic beam with velocity 1000 m/sec that perpendicularly (to eliminate the first-order Doppler effect) intercepts a laser beam 1 centimeter in diameter and frequency 5×10^{14} hertz (orange light). The sec-

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ond-order Doppler shift is about 2.7 kilohertz and the transit time broadening is about 15 kilohertz, both within the reach of existing laser technology.

A way to slow atoms (and much less easily molecules) has been known for many years. What John Prodan, William Phillips, and Harold Metcalf accomplished at NBS was making the idea work in practice. In 1975, Theodor Hänsch and Arthur Schawlow of Stanford University proposed slowing atoms by means of the momentum imparted to an atom during the absorption of a photon. On reradiating a photon, the excited atom receives another kick, which, theoretically, could cancel out the slowing effect of photon absorption. There is, however, a net slowing effect as explained by Arthur Ashkin of Bell Laboratories in 1970. All of the momentum changes due to absorbing photons are in the same direction, the direction of the laser beam, whereas the reradiated photons are emitted symmetrically around the atom. In the case of a sodium atom moving at 1000 m/sec, it takes about 30,000 photons to reduce its velocity to zero, so the momentum changes due to reradiation average approximately zero.

It is not so easy to get the same atom to absorb and reradiate 30,000 photons. Once again, the Doppler effect is the villain. Sodium, which has a single outermost electron, is in a 3S state (principal quantum number $n = 3$ and orbital angular momentum quantum number $\ell = 0$). Absorption of a photon from a tunable dye laser lifts the atom to a 3P state ($\ell = 1$). After the absorption and reradiation of about 100 photons, a sodium atom slows enough that the frequency of the laser light it sees is shifted out of resonance with the 3S to 3P transition, so that the rate of photon absorption is greatly reduced and slowing halts.

This is exactly the situation faced by physicists in the laboratory of Vladilen S. Letokhov of the Institute of Spectroscopy in Moscow who have also published evidence for laser cooling of sodium atoms. The Soviet researchers lowered the velocity at the peak of the thermal distribution from 800 m/sec to 650 m/sec, a 20 percent reduction. The width of the velocity distribution of the slowed atoms was also narrowed by a factor of 19, lowering the effective temperature of the beam from 573 to 1.5 K.

One solution to this problem is to scan the frequency of the laser in synchronization with the slowing of the atoms in the beam, so that the laser is always on the resonance frequency. This approach is the one now being followed by Letokhov and his co-workers. It is technologically difficult because the laser must be run in a so-called dual mode fashion whereby it emits light at two frequencies, and both must scan together. The two frequencies are necessary because there are two 3S states in sodium, one for the electron spin angular momentum parallel to the nuclear spin and the other for the electron spin antiparallel to the nuclear (hyperfine splitting). If only one laser frequency is used, after only a few photons are absorbed and reradiated, all the sodium atoms find themselves in the wrong 3S state because the excited atoms can decay to either 3S state, whereas they are excited from only the one to which the laser is tuned. Because of this so-called optical pumping effect, the laser quickly becomes out of resonance and the atom-slowing process halts.

. . . the researchers played the rules of the quantum mechanics of atoms the way a concert violinist does his instrument.

The NBS method is conceptually more intricate but easier to achieve. One is tempted to say the researchers played the rules of the quantum mechanics of atoms the way a concert violinist does his instrument. "It is very pretty work," commented Schawlow. Their method makes use of the Zeeman effect in which the energy levels of quantum states are shifted in magnetic fields. Their strategy also eliminates the need for two laser frequencies. A key ingredient is the use of circularly polarized laser light.

There are three points to remember. The first is that the total angular momentum is the vector sum of the electron spin, the electron orbital, and the nuclear spin angular momenta. For the 3S state, the total angular momentum quantum number F can be 1 or 2, and, for the 3P state, F can be 0, 1, 2, or 3. The second point is that under a magnetic field, the Zeeman effect further splits each of these hyperfine states of angular momentum F into $2F + 1$ states that are labeled by the components of the angular momentum parallel to the field, m_F. The final point is that quantum mechanics allows transitions due to the absorption of properly circularly polarized light only when the difference in the m_F values of the final and initial quantum states involved is $+ 1$.

Optical pumping is overcome because, when the laser is tuned to excite the transition from the 3S ($F = 2$, $m_F = 2$) to the 3P ($F = 3$, $m_F = 3$) state, the $\Delta m_F = + 1$ selection rule ensures that no other transition is accidently excited, and a similar selection rule holds for the decay of the 3P state, so that the only state the reverse transition can go to is the starting one.

To keep the laser frequency in resonance with the atoms as they slow down, the NBS physicists used a specially wound solenoidal magnet. In this way, they reduced the strength of the magnetic field and hence the energy difference between the 3S and 3P states along the length of the magnet. The variation of the field is such that the reduced Zeeman splitting of the energy levels exactly matches the reduced Doppler effect as the atoms slow down.

In operation, the experiment goes as follows. The sodium atoms emerge from an oven at a temperature of 950 K with a thermal distribution of velocities centered near 1000 m/sec. The beam enters the solenoidal magnet from the end where the field is the highest, and the laser, tuned to about 5890 Å to be in resonance with atoms slightly slower than those with the maximum velocity, shines in from the opposite end. All atoms faster than those for which the laser is tuned pass through unaffected. All others begin absorbing and reradiating the laser light as soon as they reach a position along the magnet for which resonance holds. From then on, they continue to be slowed by the laser.

To monitor the slowed atoms emerging from the magnet (60 centimeters long in early experiments and now 110 centimeters long), a second laser beam crosses the path of the atomic beam at a small angle while the cooling laser is turned off. The Doppler-broadened absorption spectrum excited by this probe laser gives the velocity profile of the slowed sodium. The observation region is 40 centimeters from the end of the magnet.

In the first round of experiments with the short magnet (maximum field of 0.06 tesla), Phillips and Metcalf were able to get sodium atoms to absorb about 15,000 photons and slow to 60 percent of their initial thermal velocity. More recently with the longer magnet (maximum field of 0.16 tesla), Prodan, Phillips, and Metcalf achieved much greater cooling. The slowest atoms were moving at 40 m/sec.

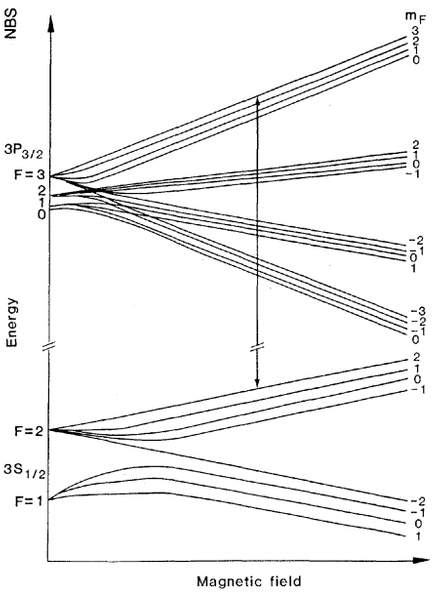
What could one do with such slow-moving atoms? Several ideas come to

mind immediately, says John Hall of the National Bureau of Standards in Boulder, Colorado. "Things that we have been daydreaming about since the first atomic clocks, we may be able to do in the next 5 years," he adds.

As for atomic timekeeping itself, there is the possibility of a 100-fold improvement. The present time standard is based on a microwave (9.192 630 770 gigahertz) transition in a beam of cesium atoms, specifically the $F = 3$, $m_F = 0$ to $F = 4$, $m_F = 0$ hyperfine transition in the 6S ground state of cesium-133. Except for incremental progress, the accuracy of clocks of this type has been "limited" to about 1 part in 10^{13} for several years. The stumbling block to increased accuracy is analogous to the transit time broadening of spectral lines discussed earlier. There are two solutions: lengthen drastically the path of the cesium beam, which is impractical as cesium clocks are already over 5 meters long, or slow down the atoms by the same factor.

Many researchers would like to see an optical rather than a microwave frequency standard because, for the same $\Delta\nu$, the relative accuracy $\Delta\nu/\nu$ is a factor of 10^5 better. Although one could make a remarkable optical frequency standard, using it for timekeeping is not so straightforward. The problem is that high speed electronic circuits to count directly the cycles do not now exist for such high frequencies.

The kinds of optical transitions that would be of interest are those to excited states that are very long lived. The ultimate limit in the uncertainty in the energy of a quantum state comes from a relationship similar to the Heisenberg uncertainty principle, $\Delta E = h/2\pi\tau$, where h is the Planck constant and τ is the lifetime. Since $E = h\nu$, the uncertainty in the energy also gives the width of the spectral line due to the transition to this state. A transition to a state with a lifetime of 1 second would have a spectral line less than 1 hertz wide. (The lifetime of the sodium 3P state is 16 nanoseconds.) Such long-lived quantum states of atoms are those to which quantum mechanical selection rules "forbid" transitions, which means the transition probabilities are very much lower than usual. Phillips and Hall will be collaborating in examining suitable atoms such as silver that simultaneously have a strong "allowed" transition, so that cooling can be accomplished, and a weak, forbidden transition to serve as the frequency standard. Recently, Letokhov and V. G. Minogin of the Institute for Spectroscopy have also proposed magnesium-24, calcium-40, and strontium-88 as candidates for optical frequency standards.



Zeeman effect in sodium

The energy of each quantum state shifts linearly with the strength of the applied magnetic field, but the slope of the shift depends on the electron orbital and spin angular momenta. The frequency of the laser-cooling transition (arrow) thereby increases as the field strength is raised.

Forbidden transitions could also play a role in testing fundamental physical theories. For example, the 1S to 2S transition in hydrogen (natural linewidth about 1 hertz) has long been of interest because the energy of the transition can be used in measuring small corrections to the energy of the 1S state that are predicted by quantum electrodynamics, the quantum field theory of the interaction between electrically charged particles. In fact, one of the reasons for the development of quantum electrodynamics was to explain the discrepancy between the predictions of the older version of the quantum theory of electromagnetic interactions and the experimental measurement of a similar shift (Lamb shift) in the hydrogen 2S state energy.

Some years ago, Carl Wieman and Hänsch at Stanford used two-photon absorption in a hydrogen discharge to obtain directly a value for the 1S to 2S transition that they then combined with another measurement to find the hydrogen 1S Lamb shift. The two-photon technique overcomes the first-order Doppler shift. An even more sensitive test of quantum electrodynamics would come from a similar measurement in positronium, the bound state of an electron and positron. Because there is no large nucleus to contend with, the calculations are subject to fewer complications than in hydrogen or any atom. This spring, Steven Chu and Allen Mills of Bell Laboratories reported the first measurement of the 1S to 2S transition in positronium, also by a two-photon absorption technique. Hall says that, if an atomic beam experiment with laser-cooled positronium were possible, so that even the second-order Doppler effect is reduced, it would make "a very definitive test of quantum electrodynamics," because theorists cannot hope with present techniques to calculate the number of terms in the perturbation series needed to make the theory as accurate as experiment.

The ultimate spectroscopic object is a single atom at rest. Physicists have, in fact, trapped single ions and then reduced their speed by laser cooling, an idea that was proposed by Hans Dehmelt of the University of Washington and David Wineland of NBS at Boulder in 1975. In 1980 Wineland and Wayne Itano at NBS laser-cooled magnesium Mg^+ ions to a very low temperature. More recently, Warren Nagourney, G. Janik, and Dehmelt of Washington have laser-cooled a single Mg^+ ion to an effective temperature of 0.005 K. Laser-cooled ions are also candidates for atomic timekeeping.

Atoms, being electrically neutral, cannot be trapped as readily as ions, but it is still possible, provided they are first cooled by the laser technique. Among proposals for trapping of neutral atoms are those of Letokhov and Minogin of the Institute for Spectroscopy and of Ashkin at Bell Laboratories. These investigators propose the use of the radiation pressure of laser light to accomplish the trapping. The idea is that there is a second force on atoms due to laser radiation in addition to that which accomplishes the cooling. The second force exists only when there is a gradient (spatial variation) in the electric field due to the laser beam. For laser light with a frequency below the resonance frequency, this force focuses the atoms in a beam to a smaller cross section, whereas for a frequency above resonance, the force pushes the atoms away (defocuses them).

Experiments at Bell Laboratories by John Bjorkholm, Richard Freeman, Ashkin, and D. B. Pearson demonstrated both these effects on sodium atoms. The researchers did not construct a trap, however, because laser cooling of atoms had not yet been achieved and fast atoms would not stay in the trap. Phillips says the NBS group will be trying to carry out Ashkin's laser-trapping scheme on their cooled sodium atoms.

—ARTHUR L. ROBINSON