swer: about 40 $\mu$K compared to the expected 240 $\mu$K.

It didn't take long for researchers both to confirm the results and to come up with an explanation for it: The expected low temperature limit had been calculated for a two-level atom, but with its Zeeman level structure, the sodium atom has far more than two levels. Cohen-Tannoudji and Dalibard at ENS and Chu, by then at Stanford, came up with an explanation that involves a complex combination of optical pumping, polarization gradients of the light field and displacements of energy levels by light—the so-called light shifts that had been discovered by Cohen-Tannoudji during his thesis work. The sub-Doppler cooling mechanism results from correlated spatial modulations of the light shifts of two ground state Zeeman sublevels, $g_1$ and $g_2$, and of the optical pumping rates between these levels. Suppose a moving atom is in, say, ground state $g_1$, at a position where the energy of this sublevel is at a minimum. As the atom moves, it must climb a potential hill, losing thermal kinetic energy in the process. At the top of this hill, the atom has a large probability to be optically pumped into the other sublevel, $g_2$, corresponding to the bottom of a valley. From there, the sequence repeats itself, leading to a very efficient decrease of the atomic kinetic energy. Because the atom is forever fated to climb potential hills, Cohen-Tannoudji has dubbed this process "Sisyphus cooling." (See the article by Cohen-Tannoudji and Phillips in PHYSICS TODAY, October 1990, page 33.)

The ENS group had earlier worked on another type of Sisyphus cooling appropriate to a two-level atom in a high intensity laser standing wave. Cohen-Tannoudji and Dalibard showed that its interpretation is particularly clear in the "dressed atom" picture developed over the last 30 years. This high-intensity Sisyphus cooling was implicitly contained in very early theoretical papers by the late Russian physicist A. P. Kazantsev, although he did not explain the physical mechanism.

### Subrecoil cooling

Having beaten the limitation on Doppler cooling, researchers now expected to hit another: the recoil cooling limit. The speed of an atom should not be less than that imparted by a single photon recoil. By the early 1990s, three groups—at ENS, NIST and the University of Munich—had cooled atoms close to the recoil limit by confining the atoms in an optical lattice—a grid of potential wells much like an egg carton formed by the standing waves of interfering laser beams. (See PHYSICS TODAY, June 1993, page 17.) Lekokhov had suggested such an optical confinement in 1968.

The recoil limit can be circumvented if one can somehow isolate any atom that happens to be nearly at rest and prevent it from absorbing any more photons. Then one can pick off only the atoms at the low end of the velocity distribution and discard the rest. To accomplish this, Cohen-Tannoudji, Alain Aspect and their colleagues formed a dark state—that is, a state in which the atom cannot absorb or emit any photons. Together with Ennio Arimondo of the University of Pisa, the ENS team found a way to make the dark state velocity dependent. During their random walk in velocity space, atoms fall into these dark states, where they pile up and remain trapped. The ENS group used this technique of velocity-selective coherent population trapping in 1995 to achieve three-dimensional subrecoil cooling of helium atoms, reaching temperatures of 180 nK, 40 times below the recoil limit. (See PHYSICS TODAY, January 1996, page 22.)

Cohen-Tannoudji told us that his lab has recently developed a new method for measuring ultra-low temperatures and observed values in one dimension that were a thousand times lower than the recoil limit. Cohen-Tannoudji, Aspect, Jean-Philippe Bouchaud and François Bardou have also developed a new theoretical approach based on Lévy flights that provides a quantitative understanding of the ultimate limits of subrecoil cooling.

Chu, working with Mark Kasevich (now at Yale University), approached subrecoil cooling in a different way. The basic requirement, Chu points out, is to prevent the slowest atoms from absorbing more light. Usually the linewidth of an optical transition limits how precisely one can address atoms in different velocity classes. By using a two-photon Raman transition between two ground states of the atom, Chu and Kasevich avoided this limitation, and they used this excitation method to push atoms to ever lower velocities without disturbing the very coldest ones.

The subrecoil cooling was done using an atomic fountain, in which the cooled atoms are propelled upwards, passing through a microwave cavity both on their way up and on their way down. Chu, Kasevich and Ralph DeVoe (IBM's Almaden Research Center) built a fountain of sodium atoms in 1989. The cesium fountain built by Christophe Salomon (ENS) and André Clairon at the Observatory of Paris is at present the most precise atomic clock in the world, with an accuracy of $2.10 \times 10^{-15}$.

### Early careers

A native of Saint Louis, Chu earned a PhD in physics from the University of California, Berkeley, in 1976 and stayed there as a postdoc before going to work at Bell Labs in 1978. He went to Stanford in 1987.

Born in Algeria, which was part of France at that time, Cohen-Tannoudji went to Paris in 1953. He received a PhD in physics from the Université de Paris in 1962. In an overlapping time period (1960–64) he was a research attaché at the Centre Nationale de Recherche Scientifique. Cohen-Tannoudji became a professor at the Université de Paris in 1964 and was elected to the Collège de France in 1973.

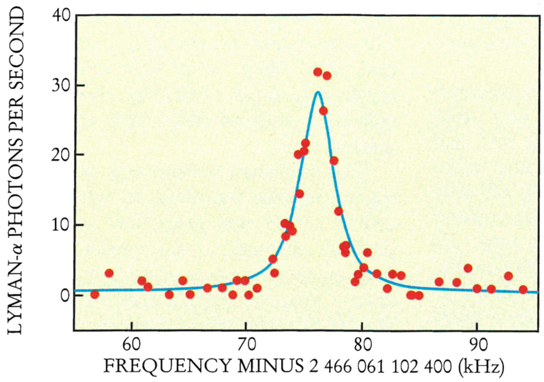
Phillips, who was born in Wilkes-Barre, Pennsylvania, received his PhD from MIT in 1976. After two years as a postdoc there, Phillips went to what was then NBS, where he has stayed. He brought to NBS the vacuum chamber he built for his thesis and used it for most of the experiments described here.

**Barbara Goss Levi**

# Optical Frequency Measurement Is Getting a Lot More Precise

A new trick for the repeated halving of optical frequency intervals now permits the measurement of optical atomic transitions with unprecedented accuracy.

At the Max Planck Institute for Quantum Optics in the Munich suburb of Garching, Theodor Hänsch and colleagues have measured the ultraviolet transition frequency between the 1S and 2S states of atomic hydrogen to be $2.466\,061\,413\,187\,34(84) \times 10^{15}$ Hz. With an uncertainty of only 3 parts in $10^{13}$, this result exceeds the accuracy of the best previous measurement of the 1S–2S transition by two orders of magnitude. It is, in fact, the most accurate measurement to date of any frequency in the visible or ultraviolet.[1] It's so accurate that simply repeating the measurement a year from now would provide a better and more direct verification (or falsification) of the constancy of the fine-structure constant




**Resonance curve** for the 1S→2S excitation in atomic hydrogen. The absolute frequency scale, uncertain to only ± 640 Hz, was determined with the optical-interval divider chain developed at Garching. This curve shows only the excitation between $F = 1$ hyperfine states. The resonant frequency quoted in the text adds, by convention, a correction for the other ($F = 0$) hyperfine states. (Adapted from ref. 1.)

over cosmological time than any astrophysical data we have.

Dirac, among others, conjectured that the fundamental constants might be varying very slowly. But that's certainly not a hot topic at present. "Of course, it's not why we developed this high-precision technique," Hänsch told us. "But if it lets us do the best test ever, we should."

## The problem

The general problem addressed by the Garching group is the difficulty of measuring optical frequencies with a precision adequate for the scientific and technological tasks at hand. Traditional laser wavelength measurement, which is essentially counting interference fringes in space and splitting the last wave, runs out of steam at about a part in $10^{10}$.

One can measure gigahertz microwave frequencies to a part in $10^{14}$ by electronically counting oscillations in time. That's how atomic clocks work, exploiting microwave hyperfine transitions. In fact, the standard second is now defined in terms of the 9 GHz hyperfine transition frequency of a cesium atomic clock. But terahertz frequencies in the infrared, not to mention the visible and ultraviolet, are already much too fast for electronic counting. "Nowadays we can make incredibly stable lasers with very narrow resonances," says MIT atomic physicist Daniel Kleppner. "But we can't do much with them if we don't have an adequate method for measuring the laser frequency."

Very accurate optical reference frequencies can be produced by constructing elaborate chains that start with an atomic clock and generate higher and higher harmonics in crystals and other nonlinear devices. But typically there's a terahertz mismatch between the nearest such reference and the optical freqency one is trying to measure. The *tour de force* accomplished by Hänsch and company is their demonstration of a general technique for bridging such large frequency intervals with great accuracy.

The essence of the new technique is the repeated application of a trick for coherently generating the mean between any two optical frequencies. Each so-called divider stage receives two input laser frequencies, $f_1$ and $f_2$, and forces a third laser to oscillate at the precise midpoint, $f_3 = (f_1 + f_2)/2$, by electronically phase locking its second harmonic, $2f_3$, to the sum $f_1 + f_2$ by means of a low-frequency beat signal. A cascaded chain of $n$ such stages shrinks the original frequency gap by a factor $2^n$.

## The experiment

Because the 2S state in hydrogen is very long-lived, the natural line width of the 1S–2S transition is exceedingly narrow—only 1.3 Hz. It's actually a two-photon transition, because the selection rules prohibit a single-photon jump from one S-wave state to another. Therefore the Garching group bombarded their cold atomic hydrogen beam with 243 nm photons from two opposite directions at once. This configuration has the merit of canceling out Doppler broadening to first order.

The two opposing beams were produced by injecting a single laser beam into an optical resonator. The beam source was an ultrastable 486 nm dye laser plus a crystal that generated its first (243 nm) harmonic. As the frequency of the tunable dye laser was swept through the 1S–2S resonance, the rate at which the 2S state was being excited was monitored by counting 121.6 nm Lyman-$\alpha$ (2P→1S) decays in an external electric field that mixed the 2S and 2P substates. The figure above shows the resulting 1S–2S resonance curve, only a few kilohertz wide. The problem was now to determine the absolute frequency of the resonance with high precision.

That's where the new optical frequency divider technique comes in. Hänsch and company took advantage of the coincidence that the 1S–2S excitation frequency differs by only about 2 THz from the 28th harmonic of a methane-stabilized 3.39 $\mu$m helium–neon laser that can serve as a portable reference standard when calibrated (to 3 parts in $10^{13}$) against a cesium atomic clock at the Physikalisch-Technische Bundesanstalt, the national standards laboratory in Braunschweig. To put it another way, the resonant dye-laser frequency, being one fourth of the full 1S–2S transition frequency, is in near coincidence with the portable standard's 7th harmonic.

The calibrated frequency $f$ of the He–Ne standard is about 88 THz in the near-infrared. It's instructive to write the resonant dye laser frequency as $7f-\Delta$, where $\Delta$ is the mismatch one seeks to measure between it and the standard's 7th harmonic. As a first divider stage, the Garching group split the difference between $f$ and the resonant dye laser frequency, producing the midpoint frequency $4f - \Delta/2$.

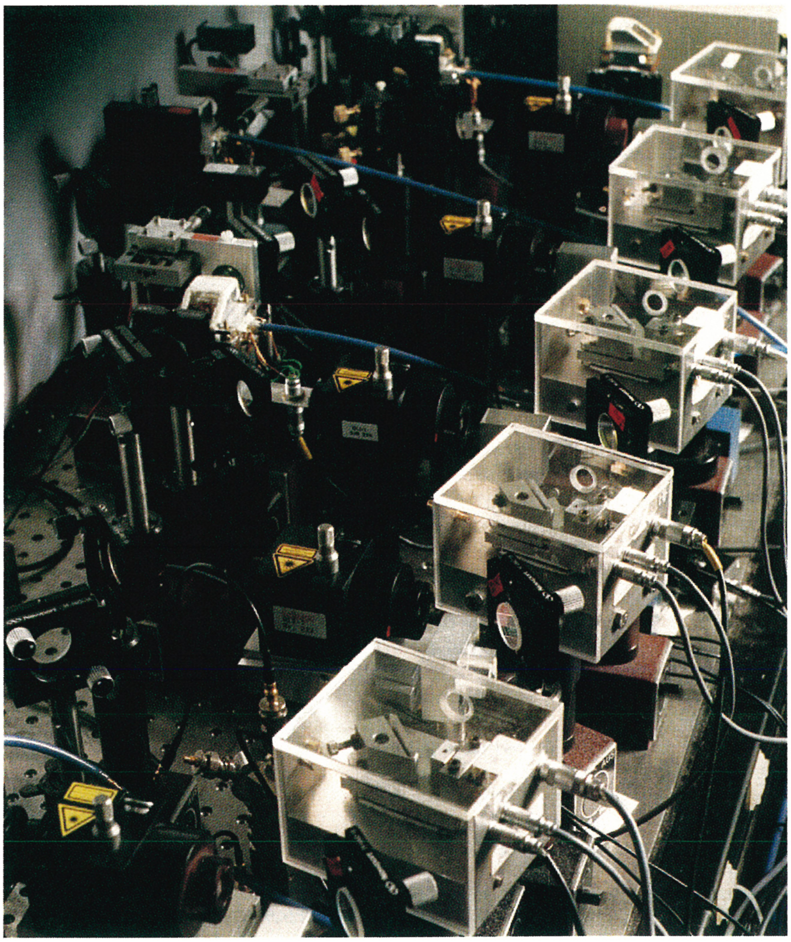
For further comparison they then generated $4f$, the fourth harmonic of the He–Ne reference, through the intervention of an AgGaSe crystal and a powerful phase-locked color center laser. With four additional cascaded divider stages they then shrank the difference between this 4th harmonic and $4f - \Delta/2$ by a factor of 16, producing a final beat frequency of about 66 GHz, low enough for standard microwave frequency counting techniques.

## Testing QED

"Our high-precision measurements in the last few years seem to have stimulated a renaissance of quantum electrodynamics calculations," Hänsch told us. "Calculating small higher-order QED effects can yield surprises. But the calculations are extremely involved, and theorists don't like to undertake them unless there's sufficiently precise data to compare them with."

The new Garching result improves somewhat on the best previous determination of the Rydberg constant. It also yields a precise new measurement of the 1S state's Lamb shift, whose agreement with the theoretical value is only on the ragged edge of consistency. "That's less likely to be a problem with the theory," suggests Hänsch, "than with the measured charge radius of the proton, which enters the QED calculation as an external parameter known only to within 10%. You can think of our result as a new measurement of the charge radius." One would like to be able to compare it with more precise measurements of the proton charge radius by new electron scatter-

OPTICAL FREQUENCY-INTERVAL divider chain now used in Theodor Hänsch's Garching lab has replaced the large, expensive lasers of reference 1 with the small grating-stabilized diode lasers seen in the 10-cm-long lucite boxes arrayed at right.



ing experiments or by spectroscopy with muonic atoms.

In recent months the Garching group has succeeded in narrowing the 4 kHz of the published resonance curve on page 20 down to only 1 kHz. This they accomplished by chopping the laser illumination into pulses and then imposing a time delay that admits only the slowest hydrogen atoms in the beam. That selection minimizes both second-order Doppler broadening and the "transit broadening" dictated by the uncertainty principle. Hänsch and coworkers have also employed an electro-optic "comb generator" to convince themselves that the divider stages don't lose even a single optical cycle.[2]

## Spreading the technique

"If Hänsch's technique can be made practical and portable, we'd be standing first in line to use it," says Kleppner. "But right now his laser chain is so big and complex that I don't know of any American lab that could reproduce it in the present funding climate. The US used to be in the forefront of atomic clock development. But with our declining support, the leadership has passed to Germany and France. Optical frequency research is a perfect example of a new technology being spawned by basic research."

A senior scientist at the US National Institute of Standards and Technology was recently overheard to say, "If anyone at NIST admitted he was setting out to do something as pure as testing QED, he'd be in trouble." But beyond its purely scientific value, the ability to measure optical frequencies to high precision should give us better atomic clocks for a myriad of practical applications. "With the $10^{10}$ Hz frequency of a cesium atomic clock," explains Hänsch, "you have to wait hours to get a $\Delta t$ precision of $10^{-14}$. But with a clock based on optical transitions, you could get $10^{-15}$ in one second."

"To make our new technique accessible to other labs," Hänsch told us, "we want to replace all our big, costly lasers with small, compact semiconductor diode lasers. We're already using such diodes in our latest frequency divider chain [see the photo above]. The special grating-stabilized diode lasers we've designed are now being marketed by a German firm."

BERTRAM SCHWARZSCHILD

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# New Results Suggest X-Ray Emission Is a Common Property of Comets

> *The brandisht Sword of God before them blaz'd*
> *Fierce as a Comet; which with torrid heat,*
> *And vapour as the Libyan Air adust,*
> *Began to parch that Temperate Clime . . .*
> —J. Milton, *Paradise Lost*

Comets—dubbed "dirty snowballs" by comet guru Fred Whipple—are among the last celestial bodies you'd expect to emit x rays, which typically come from matter at least as hot as $10^6$ K. But last year, to the surprise of astronomers, Carey Lisse (University of Maryland) and Mike Mumma (NASA's Goddard Space Flight Center) discovered faint x-ray emission from comet Hyakutake. They observed the photogenic comet with the ROSAT satellite as the comet flew by Earth in March 1996.[1] That same month, Mumma and Vladimir Krasnopolsky (Catholic University of America) detected the comet with the Extreme Ultraviolet Explorer (EUVE) satellite.[2]

Spurred by ROSAT's discovery, Konrad Dennerl, Jakob Englhauser and Joachim Trümper—all from the Max Planck Institute for Extraterrestrial Physics (MPE) in Garching, Germany—trawled through the archives of ROSAT's 1990–91 all-sky survey and came up with four more x-ray emitting