balloon had completed its 10.5-day circumpolar ride on the south-polar stratospheric vortex, the instrument was parachuted back to Earth only 30 miles from its McMurdo launch site. Boomerang is a large international collaboration headed by Paulo de Bernardis (University of Rome) and Andrew Lange (Caltech).

Maxima (Millimeter Anisotropy Experiment) was launched on its one-night flight from the National Scientific Balloon Facility in Palestine, Texas. The group's leader is Paul Richards (Berkeley). The two experiments, with very similar instruments and considerable personnel overlap, have their common origin in 1992, when Lange, Richards' former student, was still at Berkeley. The idea was to build a balloon-borne microwave telescope with sufficient angular resolution and dynamic sensitivity to resolve the fluctuation spectrum of the CMB.

As the project evolved and the number of players grew, it diverged into two distinct experiments, with somewhat different strategies. Both are microwave telescopes that scan the sky and focus the radiation onto an array of bolometers sensitive to different frequency bands. The resultant heating of these very sensitive "spider web" bolometers, all built at Caltech's Jet Propulsion Laboratory, measures the incident intensity. Mapping the sky at different frequencies—from 100 to 400 GHz—helps the observers distinguish the true cosmic microwave background from extraneous foreground sources.

The Boomerang group undertook to brave the rigors of the Antarctic primarily to gain the advantage of longer flight time and thus greater sky coverage. Their 1998 flight mapped about 3% of the full sky. The Maxima collaboration, taking advantage of its more convenient launch site festooned with dogwoods, chose to incorporate elaborate cryogenics to enhance the sensitivity of the bolometers. Furthermore, Maxima carried star-tracking instruments to facilitate its pointing precision. It's hard to track stars when the sun is shining 24 hours a day in the antarctic summer.

THE BOOMERANG BALLOON, minutes before launch in December 1998 from the US Antarctic base at McMurdo. By the time it reaches its 40 km cruising altitude, the balloon will have expanded a hundredfold. In the background is the active Mt. Erebus volcano.

The two balloon instruments will fly again. And both groups still have lots of data yet unanalyzed from their 1998 fights, which should let them determine the power spectrum out to $l = 1000$. With the launch of NASA's MAP satellite next spring, we should have year-round full-sky coverage of the CMB from this very sophisticated instrument's unobstructed perch at the Lagrange point L2, a million miles antisunward from Earth.

BERTRAM SCHWARZSCHILD

References

1. Boomerang collaboration: P. de Bernardis *et al.*, Nature **404**, 955 (2000), and A. Lange *et al.*, http://xxx.lanl.gov/astro-ph/0005004.
2. Maxima collaboration: S. Hanay *et al.*, http://xxx.lanl.gov/astro-ph/0005123, and A. Balbi *et al.*, http://xxx.lanl.gov/astro-ph/0005124.

An Atom Is Trapped by the Field of Just One Photon

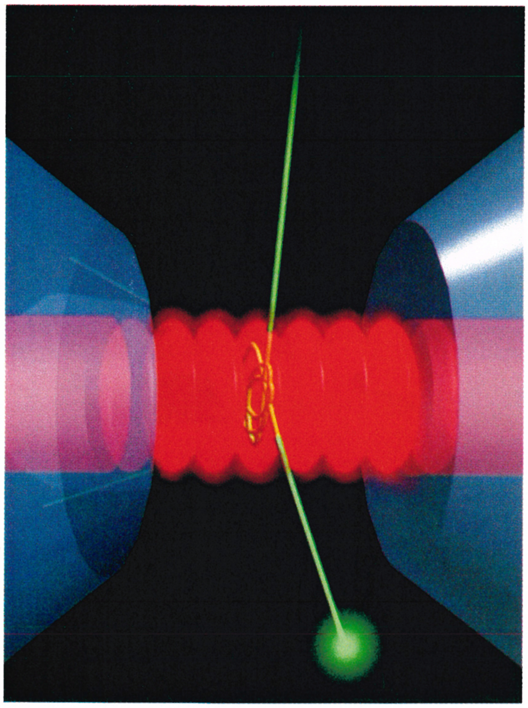
The field of a single photon can not only trap atoms but also signal its position.

Researchers have been pushing atoms around with laser beams for many years, cooling them to record low temperatures and capturing them in confined spaces. Most such efforts require many photons. The field of a single photon is not generally strong enough to corral an atom—unless, that is, the light field is enhanced by confinement within a tiny cavity and the atom enters at a crawl. Then the coupling energy of the atom to the field can exceed the atom's kinetic energy, and the atom can become ensnared. A group from Caltech and the University of Auckland,[1] and also a group at the Max Planck Institute for Quantum Optics in Garching, Germany,[2] recently created the required conditions by combining cavity quantum electrodynamics with laser trapping and cooling; both groups succeeded in confining single atoms within optical cavities with an average of one photon in the cavity.

The photons in these experiments played a double role, not only trapping the atom but giving information about its position. By monitoring the rate of transmission of photons through the cavity, the Caltech–Auckland experimenters could infer the atom's orbit-like motion within the cavity. Getting this result required the Caltech team to build an exceptionally small cavity that is strongly coupled to the atom. (In earlier work, Caltech researchers had tracked, but not trapped, single photons as they passed through a cavity.[3]) Team leader Jeffrey Kimble said that he and his colleagues are now working to add feedback to control the motion and extend the atom's lifetime in the cavity.

The top figure on page 20 is an artist's rendering of the experiment: The cavity consists of parallel half-silvered mirrors. Laser light (red beam) traveling along the cavity axis sets up a standing wave within the cavity. Atoms (green) released from a magneto-optical trap fall through the cavity region and become trapped. Yellow path indicates the trajectory reconstructed from the passage of an atom through the cavity.

The figure shows a continuous laser beam shining through the cavity rather than a single photon bounding around inside of it. That's because the lifetime of a photon in the cavity

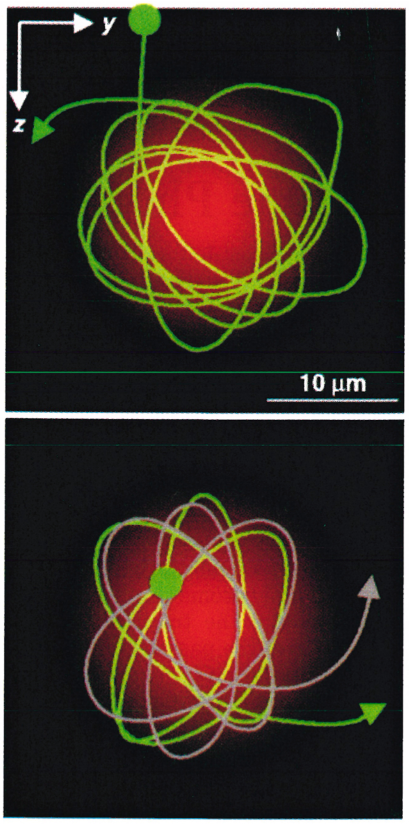


Atom trapped by photon field. Laser light (red beam) traveling along the axis is trapped between two parallel half-silvered mirrors and sets up a standing wave between them. Laser intensity is low enough that only one photon, on average, occupies the cavity at any time. Slow atoms fall through into the cavity region (green path), becoming trapped by the photon field. Yellow path indicates the trajectory reconstructed from the 1-ms passage of an atom through the cavity. (Figure courtesy of Caltech.)

is so much briefer than the time for an atom to transit the cavity that one needs a steady stream of single photons to exert on the atom an average dipole force equivalent to that of a single photon.

The experiment by the Max Planck group was similar, except that an atomic fountain directed the atoms upward into the cavity. In the cavity used by this group, the quality factor Q was about ten times higher, meaning that it held each photon longer, but the coupling of the atom to the cavity field was seven times lower. Because of the weaker coupling, diffusion plays a much larger role in the atom's motion than does the dipole force of the photon. The trajectory is consequently more irregular and can't be accurately reconstructed. The researchers did, however, use information from the outgoing photons to infer that the atoms were jumping between antinodes (points of maximal amplitude) along the cavity axis. Group leader Gerhard Rempe told us that "the light forces in these experiments are distinctively different from those in free space or in the usual enhancement cavities, not just because they are exerted by a single photon but because the atom's strong coupling with the cavity gives rise to a quantized field with photon number fluctuations different from those of a laser beam. For us, this increases the momentum diffusion and leads to novel cavity-mediated friction forces, which cool the atom into the antinodes."

Serge Haroche of the Ecole Normale Supérieure in Paris noted that in these experiments, the field of a single photon is enough to trap an atom and to affect considerably not only its internal state but also its external motion. In 1991 Haroche and several colleagues[4] and, independently, Berthold-Georg Englert and collaborators,[5] had thought about using the field of a single photon to trap atoms in a cavity, but they had in mind the field of microwaves, for which the coupling energies are impractically small.



Reconstructed Trajectories of atoms trapped in a cavity by a single photon field, in a plane perpendicular to the cavity axis. **Top:** The path (green) of an atom inferred from the cavity photon transmission rate. **Bottom:** Simulated atomic trajectory (gray) and reconstruction of the same trajectory based on the simulated cavity transmission rates (green). (Adapted from ref. 1.)

While the recent experiments don't have any immediate application to the distant goals of quantum computation and quantum cryptography, any progress in confining a single atom within a cavity is a step in that direction.

Strong atom–cavity coupling

Both experiments begin with high finesse cavities—that is, highly reflective mirrors between which photons make hundreds or thousands of round-trips before escaping from the cavity. These cavities must also be small enough to concentrate the electric field of a single photon to the point where it can exert an appreciable mechanical force on an atom (the force results from the exchange of a photon between the atom and the cavity as the atom emits and absorbs the light). To borrow an analogy from Caltech graduate student Christina Hood, the atom and cavity are bound by exchanging a photon, much as two atoms are bound in a molecule by sharing an electron. The smaller the cavity volume, the more frequent the exchanges and the stronger the coupling. The coupling strength is measured by the parameter g_0, which is half the rate of exchange of a photon between the atom and the cavity field. To trap an atom with strong coupling, g_0 should appreciably exceed both the cavity decay rate and the rate of spontaneous emission. The Caltech cavity meets this criterion with mirrors set just 10 microns apart.

In both experiments the atoms were cooled in magneto-optic traps and sent into the cavities with entrance speeds at or below 20 cm/s. The corresponding kinetic energy for the cesium atoms used in the Caltech–Auckland experiments was 0.46 mK, well below the atom–cavity coupling energy, given by $\hbar g_0$, of 5.3 mK. In the Garching measurements, the energy of rubidium atoms was 0.1 mK compared to the atom–cavity coupling of 0.8 mK.

When an atom entered a cavity, it modified the resonant properties of the cavity. In both experiments, the field was stronger when the atom was near the cavity axis and grew weaker as the atom moved outside the cavity. Thus, as the atom changed position, it altered the resonant frequency of the atom–photon interaction, which in turn affected the transmission rate of photons through the cavity. In that way, the transmission intensity could neatly track the radial position of the atom.

The Caltech–Auckland experimenters monitored the intensity of the photons coming out of the cavity by a heterodyne detection scheme, whereas the Garching researchers detected the individual photons. Both experiments began with the photon field in the cavity well below an average occupancy number of one, just enough to sense the arrival of a single atom. That signal triggered an increase in the laser intensity in the cavity, trapping the atoms with the higher fields for average times on the order of a few hundred microseconds.

Working backward

Because the photon transmission rate depends on the atom's radial position, the Caltech–Auckland team developed an algorithm for working backward from the measured transmission to determine the actual atomic orbit, which was predominantly in the transverse plane. Reconstruction was possible only because of the strong coupling provided by the single photon field. The dipole coupling force, which conserves the atom's orbital angular momentum, exceeds more diffusive forces, which change the angular momentum. By extensive measurements and simulations, Kimble and company have carefully verified that the angular momentum does indeed vary slowly along the orbits.

The bottom figure on page 20 shows one such reconstruction, which has a spatial resolution of about 2 μm over a 10-μs time period. Of course, the real atom orbits can't be viewed by any existing technique, so the Caltech–Auckland group checked its calculations by thorough comparison with the simulated motion of atoms. With each simulated trajectory, the team calculated the transmission intensities one might expect for such trajectories. Finally they applied their inversion algorithm to the simulated transmission data to infer the original orbits. The procedure fails to work well when the atom has little or no angular momentum, but the experimenters know ahead of time which cases those are. In about 90% of the reconstructions they tried, the inferred trajectories came close to the simulated ones. Feedback schemes should put their reconstructions to the most stringent test yet.

The Caltech collaborators have recently done extensive modeling of the atomic trajectories both in their experiment and that of the Garching group, in part studying the extent to which the light-induced forces in the strong coupling regime are distinct from their free-space counterparts.[6]

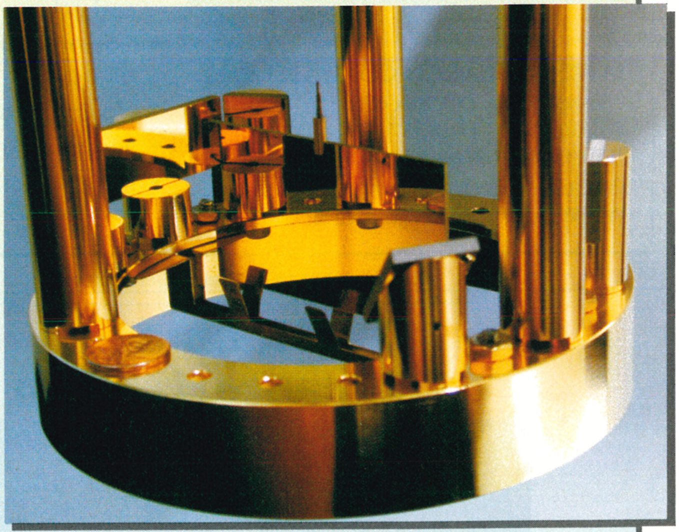
Right now, Kimble and company can treat the atom essentially as a classical particle, but as the resolution of their measurements increases, the quantum nature of the atomic motion will become increasingly important. That challenges theorists

Our Knowledge of *G* Gets Worse, Then Better

The precision with which we know a fundamental constant usually gets better with the passing years. Just the opposite, however, was happening recently to *G*, Newton's gravitational constant. In 1987, CODATA, the international arbiter of metrology, was quoting an uncertainty of ± 128 parts per million for *G*, the most poorly known of the fundamental constants. But then things got even worse. Several recent measurements have given values many standard deviations outside these limits, forcing CODATA to *increase* its assigned uncertainty to ± 1500 ppm for the latest compilation.

What was needed, obviously, was a new way of beating down the systematic uncertainties that have long plagued the torsion-pendulum experiments descended from Henry Cavendish's pioneering measurements in the1790s. Jens Gundlach and Stephen Merkowitz at the University of Washington have taken up this challenge. At the spring APS meeting in Long Beach, California, they reported a preliminary new value of *G* with an uncertainty of only 14 ppm. They find that $G = 6.674215 \pm 0.000092 \times 10^{-11}\ \mathrm{m^3/kg\ s^2}$.

Their torsion pendulum, shown below, is a mirrorlike gold-coated Pyrex rectangle hanging from an almost invisible torsion fiber and surrounded by other mirrors for a laser system that monitors any twisting. Slowly rotating on a turntable past a surrounding array of 8-kg steel balls (not shown here), the pendulum feels a periodic gravitational torque. Traditionally one measures the twisting of the pendulum as its turntable rotates uniformly past the stationary attracting balls. The most innovative feature of the new experiment is intended to eliminate uncertainties due to the torsion fiber's nonlinear response: The optical monitoring system controls a feedback mechanism that accelerates the rotation of the pendulum turntable in response to the periodic torques, thus minimizing the actual twisting of the fiber. The requisite acceleration of the turntable becomes the principal signal.



Furthermore, the array of steel balls is uniformly rotated in the opposite direction on a faster, collarlike turntable of its own, to average out the effects of any unintended environmental anisotropies and also to reduce $1/f$ noise by increasing the signal frequency. Another innovation is the pendulum's simple rectangular geometry, designed to minimize the system's sensitivity to unknown higher multipoles of the pendulum's mass distribution.

Others who measure gravity in the laboratory are certainly seeking confirmation of this claimed tenfold reduction in the uncertainty of *G*. At the same time, the experimenters are also gearing up to look for the departures from $1/R^2$ Newtonian falloff at millimeter distances predicted by string theorists trying to explain why gravity is so much weaker than any other force.

BERTRAM SCHWARZSCHILD

to think about the rules that will govern a quantum system with feedback. The Caltech–Auckland researchers call their setup an "atom–cavity microscope." The technique offers not only unprecedented resolution, Kimble stresses, but also high bandwidth.

Movement along the axis

Gerhard Rempe and his colleagues at the Max Planck Institute used simulations to explore the motion of an atom in their cavity. Their simulations of the motion of an atom in a plane perpendicular to the cavity axis confirm that the rate of transmitted photons is large or small for an atom close to or far away from the cavity axis, respectively. By studying their actual data, the researchers found indications that the trapped atom was periodically heating up as it oscillated at one antinode, then flying along the axis until it became trapped by another antinode. Their evidence for this behavior came from measurements of the correlation between photon pairs. Whenever photon pairs emerged from the cavity in close proximity, they were an indication of strong coupling and, hence, a sign that the atom was at or near an antinode along the axis. The Garching experimenters noted that the correlation rate between two photon pairs was generally just random noise, but occasionally, it would oscillate in a periodic fashion over a time span of about 20 μs before it again became random. Their interpretation of this behavior was that the periodic peaks indicated that the atom was hopping from one antinode to another until it settled into a distant antinode: Each peak in photon intensity came from the strong coupling of the atom to each antinode it passed. This interpretation is supported by the group's simulations.

BARBARA GOSS LEVI

References

1. C. J. Hood, R. W. Lynn, A. C. Doherty, A. S. Parkins, H. J. Kimble, Science **287**, 1447 (2000).
2. P. W. H. Pinkse, T. Fischer, P. Maunz, G. Rempe, Nature **404**, 365 (2000).
3. J. Ye, C. J. Hood, T. Lynn, H. Mabuchi, D. W. Vernooy, H. J. Kimble, IEEE Trans. on Instrument. and Meas. **48**, 608 (1999).
4. S. Haroche, M. Brune, J. M. Raimond, Europhys. Lett. **14**, 19 (1991).
5. B.-G. Englert, J. Schwinger, A. O. Barut, M. Scully, Europhys. Lett. **14**, 25 (1991).
6. A. C. Doherty *et al.*, http://xxx.lanl.gov/quant-ph/0006015. ■