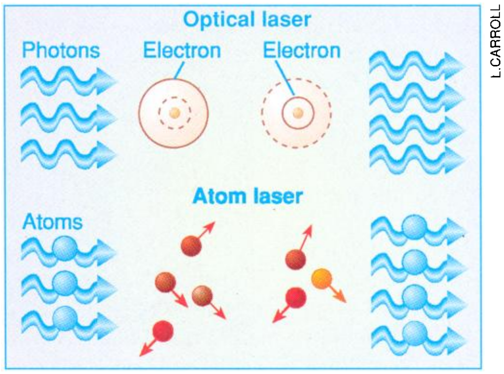
PHYSICS

Atom Laser Shows That It Is Worthy of the Name

Just over a year ago, a team of researchers at the Massachusetts Institute of Technology (MIT) announced the creation of what they called an atom laser. Purists, however, challenged the name. True, the device does produce pulses of atoms in which all the quantum-mechanical atom "waves" are coherent: They have identical wavelengths and travel in step, peak-to-peak and trough-to-trough, just like the beam of light waves from a conventional laser. One essential laser attribute seemed to be missing, however: amplification. In a conventional laser, each wave triggers another one—a process called stimulated emission—rapidly building up a powerful, coherent beam. In this issue of *Science*, the atom laser team makes good on its claim.

On page 1005, the researchers, led by Wolfgang Ketterle, report evidence that the "light" in the atom laser—atoms held in a quantum state known as a Bose-Einstein condensate (BEC)—forms through a process analogous to stimulated emission, as atoms already in the condensate help coax additional atoms into quantum lockstep. The evidence is now good enough for one skeptic. "I believe the term [laser] is appropriate," says Keith Burnett of Oxford University, adding, "As Shakespeare said: 'A rose by any other name would smell as sweet.' " Burnett and others are also impressed by the experimental finesse that this new demonstration entailed. Creating a BEC is difficult in the first place, but watching one evolve without destroying it is "fantastically challenging," says Burnett. "Ketterle's lot are just exquisitely good experimentalists."

To create a BEC—a feat first achieved in 1995 by a group in Colorado (*Science*, 14 July 1995, pp. 152, 182, and 198)—researchers cool a gas to less than a millionth of a degree above absolute zero and trap it in magnetic fields. At such temperatures, the atoms coalesce into a single quantum state and cease to be distinguishable, behaving as a single entity. Last year, Ketterle's team turned a BEC into a pulsed beam by periodically flipping the spin of the atoms with radio waves, allowing some to escape the magnetic trap. They demonstrated that the atom beams were coherent, fulfilling one laser criterion, by allowing two of them to overlap and interfere. Just like two optical laser beams, these atom beams produced an interference pattern of dark and light fringes (*Science*, 31 January 1997, p. 617).



Up the amp. Lasers amplify by enticing photons from atoms; atom lasers, by enticing other atoms.

But the term "laser," which stands for light amplification by stimulated emission of radiation, implies more. A conventional laser extracts light from a population of atoms, which are continually being pumped up into an excited, higher energy state. Photons of the laser beam bounce back and forth between two mirrors and through the excited atoms. A passing photon can stimulate an excited atom to shed energy by emitting another photon, in phase with the first and with an identical wavelength. Now Ketterle and his colleagues say that the rate at which a BEC forms in a supercold, trapped gas implies that a similar stimulated process, dubbed stimulated scattering, is at work. Although it is not exactly an amplification process, stimulated scattering can be viewed as analogous to the stimulated emission process in an optical laser.

To trace BEC formation, the team cooled a gas of sodium atoms to the threshold of BEC formation. Once the sample of about a million atoms had reached the required ultralow temperature, the researchers switched off all the cooling. They illuminated the atoms with a very faint laser beam and watched them with a

Laser Trap Gives Clearer View of Condensates

Since researchers created the first Bose-Einstein condensates (BECs) 3 years ago, they have been eagerly exploring this new state of matter and seeing what can be done with it—turning it into an atom laser, for example (see main text). But the magnetic traps used to confine the condensates put some kinds of studies off limits, because the magnetic fields freeze the spins of the trapped atoms in one orientation. Now Wolfgang Ketterle and his team at the Massachusetts Institute of Technology have removed the barrier with a new kind of trap.

As they report in a forthcoming paper in *Physical Review Letters*, they have developed a trap that confines a BEC with nothing but light beams. Now, says Ketterle, investigators will be able to play with the spins of the atoms that merge into the condensate and see what happens: "We can study 'spin waves,' we can study spin dynamics … all of a sudden we have rich physics."

To create their optically trapped condensate, the team first cooled sodium atoms in the usual way—by "evaporating" hot atoms from a gas caught in a magnetic trap, leaving a cold residue. Then they focused an extremely fine near-infrared laser beam about 6 micrometers wide into the center of the magnetic trap and switched off the fields. While previous attempts to confine a condensate in a pure optical trap failed because the lasers heated the atoms, Ketterle was able to use a very weak beam because the atoms were already precooled in the magnetic trap.

The laser field electrically polarizes the atoms, separating their positive and negative charges slightly and turning them into dipoles. The intensity of the laser beam is highest in the center of the trap, drawing one end of the dipoles toward the center and pinning the atoms in place.

In such a trap, "we can have arbitrary orientations of the atoms, while in a magnetic trap, you have 'sold off' your spin because you need stable trapping," says Ketterle. Another advantage, he says, is that the trap expels any atoms that do not belong to the condensate. The laser frequency is tuned so that any atoms with a slightly higher energy than the rest absorb radiation and get kicked out of the trap, while the atoms in the ground state are left alone.

Keith Burnett of Oxford University adds that lasers allow much more control over the atoms than magnetic fields do: "You can guide them—the laser beam is just like a tube—and you can move them around." The laser trap can also hold a greater variety of atoms, including ones that don't have a spin, says Burnett. "It is more universal as opposed to a magnetic field." –A.H.

high-speed charge-coupled device camera. "We saw that for a while nothing happened, and then slowly the action started and speeded up," says Ketterle. Many phase changes in nature happen by "relaxation," in which a system out of thermal equilibrium drops toward equilibrium almost en masse. But relaxation starts out very fast and then slows down. The accelerating pace of BEC formation implies that something different is happening, says Ketterle.

The team members believe that the BEC forms by speeding up a process of scattering. Atoms in the cooled gas want to join the condensate because it is in a lower energy state, but they need to shed some excess energy to do so. They do this by colliding with another atom outside the BEC and dumping their excess energy and momentum onto it. "One particle takes over the energy and momentum, while the other particle jumps into the condensate," says Ketterle. And, for reasons that are not yet clear, the more atoms there are in the BEC, the more other atoms want to join, causing the process to speed up rapidly. The same principle governs stimulated emission of photons: "The probability of a photon going in a direction in which there are already photons is proportional to the number of coherent photons that are already there," explains Burnett.

Condensed-matter theorists, such as Gora Shlyapnikov of the Kurchatov Institute in Moscow and Peter Zoller of the University of Innsbruck in Austria, say that the condensate growth pattern observed by the MIT team corresponds closely to some existing formation models for BECs. "The results are very convincing," says Zoller. Kris Helmerson of the National Institute of Standards and Technology in Gaithersburg, Maryland, says the study should have a practical effect, too. "By studying this process, you can find better strategies for the development of more intense sources for atom lasers," he says.

Whatever the long-term implications of the research, physicists are happy, for the time being, to watch in wonder. "Now when Ketterle presents their 'movie' of what is going on, you can sit back and enjoy the show," says Burnett. But he adds: "If you have seen all the elements that have gone into it to get to that place, it is really formidable."

–Alexander Hellemans

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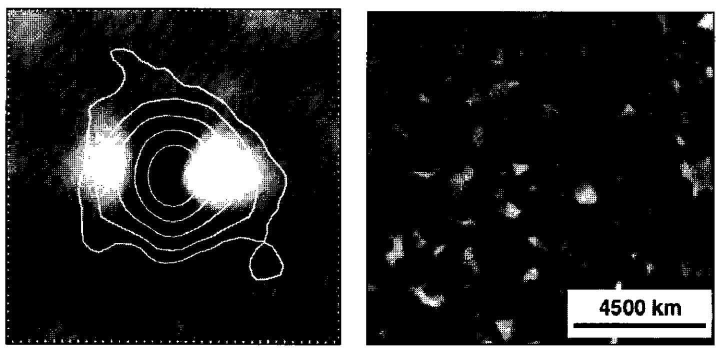
ASTROPHYSICS

Sunquakes May Power Solar Symphony

Like a quivering gong, the sun vibrates with millions of different overtones. Although astrophysicists have long exploited this ringing to glean insights into the sun's structure, its exact cause has been a mystery. Now a paper to appear in the 1 March issue of the *Astrophysical Journal* proposes that solar tremors called "sunquakes" power this resonance with bursts of sound.

The researchers—from the New Jersey Institute of Technology (NJIT); the University of Colorado, Boulder; and the National Solar Observatory (NSO)—analyzed detailed measurements of the solar atmosphere for telltale motions caused by sound. Their findings strengthen a theory that gas plunges noisily below the solar surface. Although it's unclear how these downdrafts might generate the noise, the team detected this acoustic energy feeding one type of solar oscillation. The quakes themselves could also provide a new probe for peering beneath the sun's surface.

For decades, astrophysicists have simply attributed the sun's ringing to turbulent convection near its surface, where 1000-kilometer-wide patches of hot gas called granules bubble up from the sun's interior and slam into the solar atmosphere. A twist on this theory emerged in the mid-1980s when computer models predicted that after gas cools at the sun's surface, it forms narrow plumes that plunge at supersonic speeds toward the interior—presumably unleashing sonic booms. The plunging gas might also trigger sunquakes by sucking together neighboring granules.



Sunscream. Burst contour over cool gas (close-up, *left*) hints at solar gong.

The first glimpse of these powerful internal downdrafts came in 1995, when Philip Goode of NJIT in Newark, Thomas Rimmele and Louis Strous, now of the NSO in Sunspot, New Mexico, and Robin Stebbins of Colorado observed a darkening of narrow gas lanes between granules, indicating cooling. If so, the chilled gas must fall "like a bowling ball in a swimming pool," says Stebbins.

But separating the resulting quakes from background noise in the sun's turbulent atmosphere is tricky. To do so, the team clocked the speed and direction of gas flowing at two altitudes above the sun's surface—150 and 330 kilometers—by measuring the Doppler shift of light absorbed by iron ions swirling in the sun's atmosphere. The acceleration of first the lower gas layers, then the overlying ones, suggests they were shoved by a sound wave, the researchers say. To see what might be triggering the bursts, they superimposed images of the surface beneath more than 2000 sound bursts—before, during, and after an event. The composites revealed that bursts consistently emanated from the dark lanes (see figure above). Immediately after a sound's intensity peaked, the lanes would narrow, suggesting that neighboring granules were filling a void.

Just as blowing into a trumpet won't necessarily produce a resonant tone, sound bursts on the sun's surface don't necessarily amplify solar vibrations; they have to have the right wavelength and velocity to excite the sun's natural oscillation frequencies. But the team has evidence that the quakes do excite at least one kind of oscillation, the f-mode. About 800 kilometers away from a sunquake's epicenter, "we can literally see the conversion of sound at many frequencies to sound that just belongs to the f-mode," says Goode. The team calculates that the estimated total number of quakes would have more than enough power to drive all the sun's oscillations.

The findings are "a nice illustration of a mechanism actually operating," says Peter Goldreich, an astrophysicist at the California Institute of Technology. But others are skeptical that sound bursts come from the shrieking downdrafts and thundering granules. In the composite images the team produced, the bursts aren't centered squarely on the dark lanes. That "makes me suspicious," says Tom Duvall of NASA Goddard Space Flight Center in Greenbelt, Maryland. "We don't have an explanation for that yet," acknowledges Rimmele. "We still have to investigate."

But if sunquakes are real, they might be used to probe granule structure and the local magnetic fields set up in the dark lanes, says Goode—much as seismologists on Earth detonate a charge, then study where waves resurface. Mapping this structure more finely is important because astronomers who now use oscillations to probe the sun's interior must assume that waves passing through the uppermost regions aren't much distorted. Says Phil Scherrer of Stanford University, "We're much better off if we can actually understand the surface and the sources."

–Erik Stokstad