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MIT'S Wolfgang Ketterle: New Marching Orders for Atoms

In 1995, Wolfgang Ketterle astounded the quiet world of atomic physics with the announcement that his group at the Massachusetts Institute of Technology had created Bose-Einstein condensation (BEC), the so-called "fifth state of matter" in which atoms are locked together in the lowest quantum state of the system. This achievement came on the heels of a breakthrough by a group at Boulder, Colorado, which had independently created BEC earlier in 1995. Barely two years later Ketterle was back on the front page with even more dramatic news: the demonstration of the world's first atom laser, a coherent beam of atoms in the same quantum state. In Great Britain the BBC led the early-morning news slots with Ketterle's quiet voice telling the world he could make atoms "march in lockstep." Subsequently, Ketterle became a familiar presence in *Science Watch*'s Physics Top Ten; his team's 1995 *Physical Review Letters* paper on BEC has now been cited more than 400 times (see the table on the next page, paper #1).

Experimental physicist Wolfgang Ketterle built the first atom laser in a cramped laboratory bristling with cryogenic equipment at the Massachusetts Institute of Technology, Cambridge.
Photo: Simon Mitton

A specialist in atomic physics and spectroscopy, the German-born Ketterle, 41, studied physics at the University of Heidelberg and the Technical University of Munich. His doctoral studies, undertaken at the Ludwig Maximilians University of Munich and the Max Planck Institute for Quantum Optics, Garching, were completed in 1986. Among his early accomplishments at Garching, Ketterle lists the first observation of discrete spectra of HeH, a complete analysis of the electronic structure of HeH, measurements of the lifetime of triatomic hydrogen, and spectroscopy of all the stable isotopes of H_3. Following this fundamental work, he returned for a short time to the University of Heidelberg to work on immediately applicable physics: laser diagnostics of combustion in the diesel engine. But his ambition to work on fundamental topics led to Ketterle joining the Physics Department of MIT as a research associate in 1990, following which he was appointed assistant professor in 1993.

MIT recognized Ketterle's experimental genius in July 1997 with promotion to full professor. In 1997 he shared with Eric Cornell (University of Colorado, Boulder) the Rabi Prize of the American Physical Society. The German Physical Society awarded him the 1997 Gustav-Hertz Prize. Both societies cited Ketterle's achievement in the realization and subsequent study of BEC.

▶ *Science Watch* Physics correspondent Simon Mitton spoke with Ketterle at his MIT office.

SW You've contributed to MIT becoming one of the leading centers in the world for the study of atom trapping, laser cooling, and Bose-Einstein condensate. What interested you in atomic physics

as a research field?

Ketterle: My career started out in condensed matter physics and molecular spectroscopy. I turned to atomic physics only later. My switch from molecular spectroscopy to atomic physics was influenced by the fact that I knew spectroscopy very well and looked for a new field in which to apply it. At that point I decided that atomic spectroscopy, laser cooling, and trapping were very promising fields, and I wanted to join in. I came here eight years ago as a postdoc with Dave Pritchard, where I learned a lot of atomic physics.

At that time, what problems in atom trapping and laser cooling needed solutions?

Ketterle: Laser cooling was in pretty full swing, and people had demonstrated wonderful cooling and trapping techniques. However, it was clear that some dreams had not been fulfilled. Cooling and trapping were both hitting limitations. When laser cooling was invented and pioneered in the late 80s, people were already dreaming of Bose-Einstein condensation, where new collective phenomena would show up. BEC requires extremely low temperatures and high densities, and laser cooling was, at that point, at best five orders of magnitude in phase space density away. Early on in my work with Dave Pritchard we started working first theoretically and later experimentally on how could we overcome the limitations of laser cooling.

Why didn't laser cooling get closer to the desirable conditions?

Ketterle: The limitation of laser cooling is reaching a high enough density for interesting physics. Laser cooling is great for low density, when the laser light can reach the atoms. But once you have a very high density, the laser light just gets absorbed. So although the technique was very powerful for atomic gases at low density, we couldn't explore the denser parts of phase space, which you must do to create Bose-Einstein condensate.

However, in another field of physics, the community studying spin polarization of hydrogen—which is more traditional low-temperature physics—had developed another cooling technique which does not require laser light. Evaporative cooling was pioneered here at MIT, and it simply requires elastic collisions to thermalize the gas you want to cool. This, of course, is the same phenomenon that causes bathwater or the coffee in your cup to get cold. The hot water molecules escape as steam and the remaining water gets colder and colder. It works great for atoms too, but this cooling scheme requires high densities because you need frequent collisions between the particles in order to reach thermal equilibrium. Many people perceived a gap between the densities that can be achieved by laser cooling and the (higher) densities needed to get evaporative cooling started. In 1994 we finally closed the gap between the techniques. Once we had achieved the combination of laser and evaporative cooling, it was really amazing. Within little more than a year, BEC was realized. The moment we had bridged the gap, everything just took off, at a rate of progress that took everyone's breathe away, including myself!

In the set-up at MIT we use sodium atoms and lasers operating in the visible-yellow light. Our multistage process starts with a hot atomic beam at 600 K. We cool the atomic beam by Zeeman slowing, in which the atom velocities are reduced by a counter-propagating laser beam. Then we use the standard magneto-optic trap; we employ the dark version of a technique that Dave Pritchard and I introduced. This technique involves higher densities than other traps. After additional laser cooling, we transfer the atoms to a magnetic traps. We now use a novel cloverleaf trap as a magnetic trap, something we introduced in 1996. Finally, we use evaporative cooling to achieve the density and low temperature needed for BEC.

Once you thought you had reached the critical conditions for BEC, how did you prove that the atoms were behaving coherently, which is the crucial test of the physics?

Ketterle: In the first experiment on BEC we mainly showed that the gas condensed into an extremely cold form of matter—or, to be more precise, the gas had extremely small energy content. When we released the cloud all of a sudden we could see a dense core which was almost not spreading out at all. This was the condensate!

In addition to being ultracold, the BEC gas has the property that its atoms are coherent, a feature I describe as "atoms marching in lockstep." This coherence is a different property to simply being ultracold, although the two are related. The next step was to show the coherence property directly to show that we had in effect made a matter wave. The trick to prove that was an interference experiment. We followed traditional examples from optics where you demonstrate the coherence of light by recording an interference pattern.

If you shine two coherent light beams on a screen, you get the bright and dark lines of an interference pattern. So eventually we did the same experiment with Bose condensates. We created two condensates in a special atom trap and then made them overlap, and what we saw was a regular pattern of dark and bright fringes. That was immediate and direct confirmation that we had created coherent atoms.

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What is the "effective wavelength" of the sodium BEC?

Ketterle: The periodicity of the pattern which we observed was 15 micrometers, which is around 30 times longer than visible light. The only way we could observe the interference pattern was by using light. Given that limitation we had to create a situation where the matter wave was much larger than the light waves. To put that in context, note that in a thermal gas of atoms the matter wavelength is 0.5 angstrom, which is smaller than an atom. So if you want to study or exploit the wave nature of atoms you must go to very low temperatures.

Wolfgang Ketterle's Highest-Impact Papers Published Since 1995
(Ranked by average citations per year)

Rank	Paper	Total citations	Average cites per year
1	K.B. Davis, *et al.*, **"Bose-Einstein condensation in a gas of sodium atoms,"** *Phys. Rev. Lett.*, 75(22):3969-73, 1995.	421	168
2	M.R. Andrews, *et al.*, **"Observation of interference between two Bose condensates,"** *Science*, 275(5300):637-41, 1997.	74	49
3	M.O. Mewes, *et al.*, **"Bose-Einstein condensation in a tightly confining DC magnetic trap,"** *Phys. Rev. Lett.*, 77(3):416-9, 1996.	117	47
4	M.0. Mewes, *et al.*, **"Collective excitations of a Bose-Einstein condensate in a magnetic trap,"** *Phys. Rev. Lett.*, 77(6):988-91, 1996.	106	42
5	M.O. Mewes, *et al.*, **"Output coupler for Bose-Einstein condensed atoms,"** *Phys. Rev. Lett.*, 78(4):582-5, 1997.	63	42

SOURCE: ISI's Personal Citation Report, 1981-June 1998. Legend

After the realization of BEC in your lab, and also at Rice University, Houston using ^{7}Li atoms, and NIST, Boulder using ^{87}Rb, you decided that your next goal was to build an atom laser, in which coherent matter from BEC would replace the coherent light of an optical laser.

Ketterle: Yes. An atom laser is a device that emits coherent matter waves. It is an intense source of coherent atoms. Bose condensate, with its coherent atoms, is an excellent starting point on the road to the atom laser. We had to take two further steps to make the atom laser. First we had to extract the atoms from the Bose condensate, so we added an output coupler to the magnetic trap in which the condensate was confined. An optical laser relies on mirrors which leak maybe 10% of the light. We made a leak in the trap by using a magnetic field to tilt the spins of the atoms. By controlling the spin angle we could make dollops of sodium condensate. The second step, which I've already mentioned, was the much harder part: we now had to show that the extracted atoms were truly coherent in that they had laser-like properties. Taken together, the two experiments realized the atom laser, as was reported in work that we published early in 1997. But that was just one approach. There are other atom laser concepts: all you need is an atom resonator or cavity, and you have to create a situation where you have a strong population of a single mode of this cavity.

Many people said an atom laser is impossible because you cannot amplify atoms, which would violate the conservation of mass. Here's my answer to that: an optical laser is not creating energy. Rather, it transforms an energy input into coherent radiation. Likewise the atom laser is not creating atoms; it takes atoms out of a reservoir and transfers these atoms into a single mode of the cavity. The atom laser generates coherent matter waves by transferring atoms from an incoherent reservoir into this single mode. The atom laser is definitely based on matter-wave amplification. It works by amplifying matter waves in one mode of the cavity at the expense of atoms occupying other modes.

SW ***Are there applications where a matter laser would take over from an optical laser?***

Ketterle: Well, light propagates through air whereas atoms are stuck after less than a micrometer. That means an atom laser can only operate in vacuum, so it won't lead to better CD players or supermarket scanners! Atoms strongly interact with each other—unlike photons—and they also respond to gravitational fields. So if you shoot a beam of atoms they are bent towards the Earth by gravity. In the case of light, although the same effect happens, it is usually completely negligible.

SW ***You've achieved this goal of an atom laser. When the optical laser was realized it was described as a solution in search of a problem. What are the potential applications for coherent beams of atoms?***

Ketterle: First a caveat: I like the analogy with laser light, and that is what motivates people to intensify research on the atom laser. The step from a light bulb to a laser was a major step in controlling light. Until recently in atomic physics we had only the incoherent sources. Now we have made the major step towards coherent atoms. This is important for atomic physics where we need to control light and atoms.

On the other hand this analogy might raise certain promises: even being very optimistic I would not foresee that the atom laser will revolutionize research and technology in the same way that the optical laser did. That's because you cannot send atomic beams through air and you cannot superimpose the atomic beams, because of atom-atom scattering, in the way you can combine laser beams.

The atom laser with long matter wavelengths can only be reached at extremely low temperatures. Personally I cannot see how the operation of an atom laser can be scaled up to work at higher temperatures. It will always be technologically demanding to operate an atom laser. In fact, since our publications early in 1997, my group has been working on fundamentally understanding BEC rather than rushing ahead with the atom laser. We have been looking at sound wave propagation in BEC, as well as collective excitations. The atom laser remains high on our priority list, and we need to increase the power by one or two orders of magnitude.

SW ***Right now we can say this has enlivened atomic physics because we can now control atoms in a new way. However, we are a long way from any devices or applications.***

Ketterle: We are in the early days. We have to learn how to control the atom laser. But I think the effect is so general it is hard to imagine that there won't be major applications in research, simply because the atom laser means we can control the position and motion of atoms at an unprecedented level: we are now down at the quantum level. We are approaching the theoretical limitations which are given by the quantum mechanical nature of matter. That's a major achievement—it means control of the elementary building blocks of nature. So I guess the atom laser will be used in those situations where you need precise control over atoms. For example, precision measurements, measurements of fundamental constants, or tests of fundamental symmetries.

Other areas include my dreams of atom microscopy or better deposition of atoms. I think those applications are harder because they not only need a high degree of control over atoms but they also require intensity in the atomic beam at a much higher level than we have achieved. There are many challenges but few applications. Nevertheless, as a researcher you have to be optimistic and open-minded. My philosophy will be to develop this open and exciting field and not dwell on arguments why the potential might be limited.■

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