Atom

BY JAKOB REICHEL

Magnetic fields on a microchip can produce tiny, coherent clouds of atoms called Bose-Einstein condensates. The chips could have uses in ultraprecise sensors for aircraft and in quantum computing

Chips

ULTRACOLD CLOUD OF ATOMS levitates in the magnetic field produced near the surface of a simple microchip, in this artist's conception.

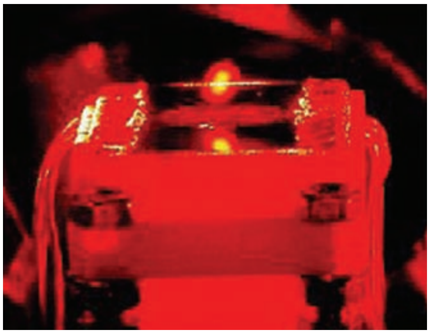
A century after its conception, quantum mechanics continues to be a disturbing theory. It tells us to think of all matter as waves, and yet in all objects that surround us these matter waves are far too small to be seen. Although the quantum laws are thought to be valid for objects of all sizes—from elementary particles to the universe as a whole—we do not usually see matter waves or any other quantum behavior in our everyday world.

In some subtle way, which physicists still do not completely understand, quantum mechanics conceals its strange effects when many particles interact in a disordered manner or when temperature rises much above absolute zero—that is, whenever things get a little bit complicated, as they usually do in the macroscopic world. As a result, quantum phenomena tend to be associated only with the world of elementary particles and with abstract thought experiments, such as the famous but mysterious Schrödinger's cat, which exists in a quantum state that is simultaneously alive and dead.

Recently, however, this picture has started to change. Physicists are learning to preserve the weirdness of quantum mechanics on larger and larger scales and to observe it in increasingly direct ways. One particularly beautiful example of this trend was the achievement of a Bose-Einstein condensate (BEC) of atoms in 1995. In a BEC, hundreds of thousands of atoms gather in the same quantum-mechanical state. Their individual matter waves all become exactly superposed. Because the resulting giant matter wave contains so many atoms, it is easy to observe: once a BEC is there, it takes hardly more than a video camera to see that matter has a wavy nature!

This unprecedented accessibility of matter waves has created a veritable BEC boom. Hundreds of researchers, theorists and experimentalists alike, who used to work in quite diverse subfields of physics, have turned their attention to the new topic. Over the past few years, BEC studies have given fresh experimental life to many quantum effects that formerly were considered very remote and inaccessible in practice. In this sense, BEC research has made quantum phenomena become more real, like a rock you can directly see and kick instead of something talked about in the abstract.

If BECs are easy to observe, creating them used to be a daunting task: the phase transition from a classical (nonquantum) atomic vapor to a condensate occurs at an extremely low temperature—usually less than a millionth of a degree above absolute zero. To achieve this temperature, the atoms must be isolated in a vacuum cell, suspended in free space by magnetic fields, and chilled by laser cooling and another technique called evaporative cooling [*see box on page 51*]. The slightest uncontrolled interaction with the room-temperature world around them would destroy the atoms' fragile quantum state. Thus, in the 50 or so research labs that are now able to produce BECs, the tiny cloud of ultracold atoms is usually surrounded by several tons of high-tech equipment. Ultrahigh-vacuum components, meticulously cleaned according to "voodoo" recipes, produce the world's best vacua and protect the atoms from the violent collisions that occur in room-temperature gases such as the air around us.



ATOM CHIP in the lab of Jörg Schmiedmayer at the University of Heidelberg traps a cloud of cold lithium atoms above its surface. The mirror image of the atom cloud is visible in the chip's shiny gold-coated gallium arsenide surface.

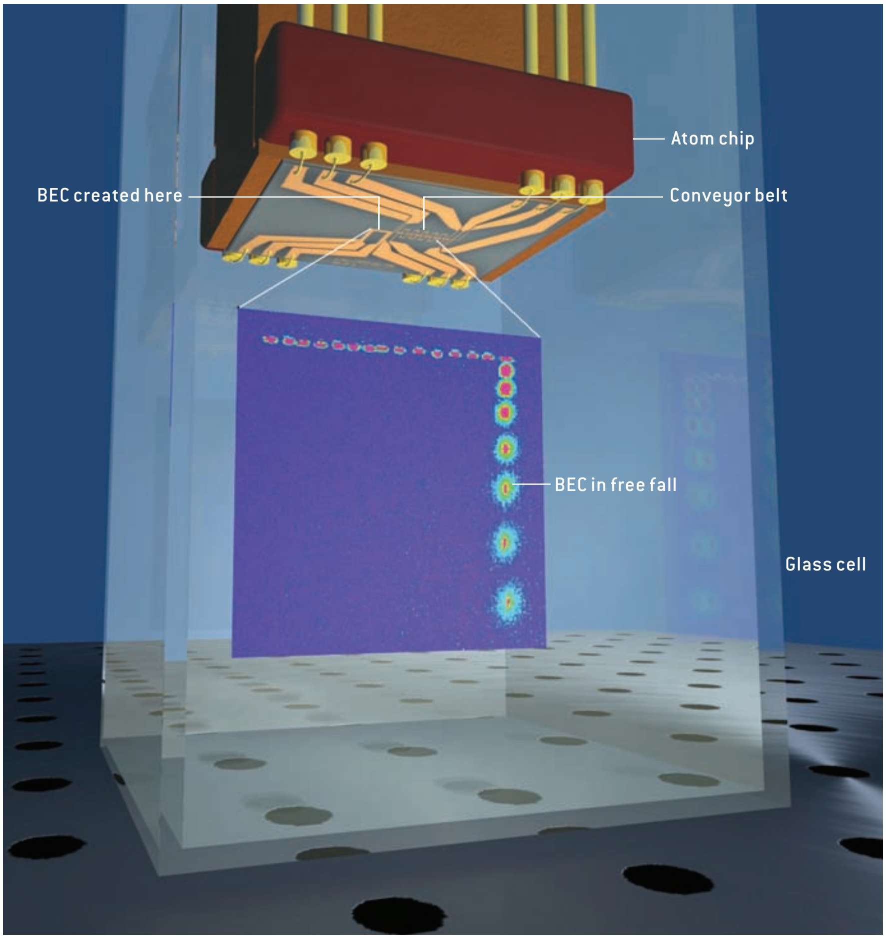
A key technique in all these experiments is magnetic trapping—the art of levitating atoms in free space with the help of magnetic fields. Evaporative cooling can work only in a trap, and magnetic traps are the ones that work best with this cooling technique. Furthermore, the stronger the trap (the more tightly the atoms are squeezed into a small volume), the faster and more efficient the cooling. Consequently, BEC researchers got accustomed to surrounding their vacuum cells with powerful but cumbersome electromagnets. To get the strongest magnetic compression, they developed heavy, water-cooled coils, often made from sturdy refrigerator tubing and consuming many kilowatts of electric power. Designing and operating these magnetic traps accounted for a significant part of the effort in BEC experiments.

In view of this experimental complexity, many found it hard to imagine that BECs could be employed in real-world applications, such as proposed portable rotation sensors, which might one day allow aircraft or submarines to navigate with unheard-of precision. Re-

Overview/*Atom Chips*

- Physicists are learning to preserve the weirdness of quantum mechanics on larger scales, which makes these phenomena easier to observe and to apply. Bose-Einstein condensates (BECs) are one such phenomenon, in which the wavy nature of matter is apparent.
- The magnetic fields on a microchip can hold a cloud of atoms suspended in a vacuum at a temperature just above absolute zero to create a BEC. Such "atom chips" are smaller than conventional magnetic traps, consume a thousandth as much power, operate much faster and require a less perfect vacuum.
- Atom chips could have applications as ultraprecise sensors for aircraft or marine navigation and for building quantum computers.

KENN BROWN (*preceding pages*); JÖRG SCHMIEDMAYER (*this page*)



ATOMIC CONVEYOR BELT can transport and precisely position a Bose-Einstein condensate (BEC). The conveyor belt is the square-tooth wire structure in the center of the chip, which produces a series of magnetic wells whose position depends on the phase of the currents in the wires. The series of images (*purple square*) was taken while the conveyor transported the condensate over a distance of 1.6 millimeters along the chip surface. After the transport, the BEC was released into free fall. The shape it expanded to was characteristic of a BEC, demonstrating that the fragile condensate state survived the transport. (The chip structure and glass cell were added to the image to clarify the position of the conveyor.)

THEODOR W. HÄNSCH

cently some remarkable developments have changed this state of affairs. In particular, we can now trap, move and manipulate the atoms with the help of microchips. A portable quantum laboratory, such as would be needed for the sensor applications, is no longer a wild dream but a very concrete research goal.

A Magnetic Landscape

HOW CAN A MICROCHIP hold and control a cloud of atoms suspended near its surface? The answer is by taking advantage of the magnetic fields it naturally creates. Microchips such as the ones found in computers contain a complex array of thousands of microscopic wires. Currents flowing through these wires produce a magnetic field. Usually nobody cares about this field—at any macroscopic distance from the chip surface, the field is immeasurably small. Very near the wires, however, the field grows at a rate inversely proportional to the distance. Within 100 microns of the chip surface, the field forms the magnetic trap that suspends the atom cloud in free space. Because the atoms are so close to the wires, less than one watt of electric power is enough to operate this magnetic trap—it could easily be run off the battery of a laptop computer. Compare this with the kilowatts that were needed in the traditional magnetic traps.

Better still, the trap is much stronger than the conventional, coil-based ones, and it can create a BEC in less than a second. Coil-based traps rarely take less than half a minute to create a condensate. This increased speed is important because experiments on BECs typically need to be repeated hundreds of times to build up good statistics for a range of experimental conditions. Every single run requires the creation of a fresh BEC, needing a batch of atoms to be loaded and trapped and cooled all the way from well above room temperature to nearly absolute zero. It also makes a big difference for the rotation sensor, where higher speed directly translates into higher precision (because it reduces noise).

The increased speed simplifies the BEC apparatus quite dramatically because the vacuum can have 100 times as much residual gas in it. The problem with a poor vacuum is that the stray remaining particles steadily deplete the cloud of trapped atoms by colliding with them, thereby knocking them out of the magnetic trap. When the cooling proceeds faster, it is okay to have more of these stray particles in the system because they have less time to do their damage. So the vacuum technology can be much simpler: the vacuum for a chip BEC need hardly be better than that inside a television tube. Thus, miniaturizing the magnetic trap allows other parts of the apparatus to be miniaturized, too.

In spite of these advantages, at first it seems outrageous to try to store a BEC—thought to be the coldest object in the universe—within a hundred microns of a room-temperature surface (that of the microchip). Such a surface constantly emits infrared radiation, which can transfer heat to anything that is nearby. Who would store ice cubes near a radiator? Consequently, the first chip-trap proposal, put forward by a group at the California Institute of Technology in 1995, involved cooling the entire chip to near absolute zero using a bulky and expensive liquid-helium refrigerator. My own group wanted to preserve the appealing simplicity of the chip approach and chose in 1997 to work at room temperature and hope for the best.

Fortunately, our ultracold atom clouds are very unlike ice cubes. A solid object such as an ice cube is a very efficient absorber of heat radiation. The gaseous atoms, however, absorb radiation only at certain sharply defined wavelengths, so the gas absorbs hardly any of the heat radiated by the chip. Today we know that all thermal interactions are negligibly weak at a distance of 100 microns and do no harm on the timescale of a BEC experiment.

When the idea of a chip trap first came up, shortly after the first BECs had been produced in 1995, a few tricky problems had to be solved before the dream could come true. First, of course, a trapping chip had to be designed and built. Learning how to do this was an enormously rewarding experience for me. I have always been impressed with the incredible pace of progress in the microelectronics industry, which faces new challenges every year but implacably overcomes them, one by one, to keep up its rate of miniaturization. As a cold-atom physicist, I had only a vague idea of the technologies behind this progress. Now I became involved with it. Talking to specialists in that field, consulting books and Web sites, I found out about thin-film hybrid devices, which feature gold conductors on little ceramic chips and can be used for atom trapping. I also learned to appreciate the vast technological culture of the microelectronics industry that usually stays behind the scenes, although we all use the electronics, from TV sets to notebook computers, that result from it.

It seems OUTRAGEOUS to store the coldest object in the universe SO CLOSE to a room-temperature surface.

Having learned how a trapping chip could be manufactured, my colleagues and I at the Max Planck Institute of Quantum Optics in Garching and the Ludwig Maximilian University in Munich were faced with the problem of loading the trap with atoms. Whether one is using a conventional coil-based system or an atom chip, before the atoms can be held in the purely magnetic trap, they must be cooled to microkelvin temperature in a magneto-optical trap (MOT). An essential element of a MOT is an array of six laser beams that bathe the atoms on all sides and from above and below. How can one implement a MOT when a chip surface gets in the way? The chip will inevitably block at least one of the beams, and the MOT no longer works.

The solution is to have a mirror coating on the chip reflect two of the beams [*see box on opposite page*]. If the lasers and the chip are oriented in the right way, the reflected beams can replace the blocked ones, and the MOT works again, producing a cloud of cold atoms right above the chip surface. A few additional details had to be taken into account (the polarization of the laser beams has to come out right), but the idea worked, and the system is now called a mirror-MOT, or a surface-MOT. Once the atoms are precooled in the mirror-MOT, loading them into the chip trap is easy: the MOT is switched off, and the current through the wires on the chip switched on. When this happens, most of the atom cloud finds itself trapped in the chip's magnetic field.

In 1998 graduate student Wolfgang Hänsel, quantum-optics wizard Theodor W. Hänsch and I employed this technique for trapping and cooling atoms in the first demonstration of an atom chip at the Max Planck Institute. Still, many researchers were skeptical about the future of the new technique for producing BECs, mainly because the chip surface is so close to the trapped atoms. In the summer of 2001 my group and that of Claus Zimmermann at the University of Tübingen, also in Germany, proved the doubters wrong and independently created BECs using microchip traps. It was a remarkable coincidence that our groups reached this long-sought breakthrough within only a few days of each other. Zimmermann (who had also been a collaborator of Hänsch before moving to Tübingen) has called it an entanglement of ideas, referring to the famous quantum-physics phenomenon. More than a dozen laboratories around the world now use atom chips for BEC experiments.

The basic atom chip requires only two or three wires in a simple arrangement to form a magnetic trap. But much more is possible thanks to another advantage of the technique—maybe the most important one: from its microelectronics ancestors, the atom chip inherits all the benefits of microfabrication technology. We can lay out the wires in any desired pattern, going around curves and meandering paths and even across one another. When currents travel through these wire arrangements, they produce a complex magnetic landscape for the atoms to explore, opening fantastic possibilities for atom manipulation.

For example, my group in Munich demonstrated a BEC "conveyor belt," using a chip whose structure went well beyond that of a simple trap [*see illustration on preceding page*]. When the currents applied to the various wires are

THE AUTHOR

JAKOB REICHEL obtained his Ph.D. from the École Normale Supérieure (ENS) in Paris. In his thesis, he used a laser-cooling method to obtain then record-low temperatures. He returned to his native Germany in 1997 to work at the Max Planck Institute of Quantum Optics in Garching and the Ludwig Maximilian University in Munich. There, together with Theodor W. Hänsch, he established a small group that pioneered the use of microfabrication methods for cold-atom manipulation. In the summer of 2004 Reichel received a European Young Investigator award and took up a position at the ENS in Paris, where he is setting up a microtrap research group. Married with a baby son, he finds inspiration playing the viola in a string quartet with good friends.

COOLING A GAS OF ATOMS

Hot gas atoms behave a lot like hard little balls—they are very classical, or nonquantum. But every atom actually has a quantum wave packet that is spread out over a small region. For hot atoms, the wave packet is tiny, but it gets larger as an atom cools down. A Bose-Einstein condensate (BEC) forms when the gas is so cold and dense that the wave packets become large enough to overlap. Then the atoms all pile up in the same quantum state—the same wave packet—merging into a unified, wavelike blob that is a Bose-Einstein condensate.

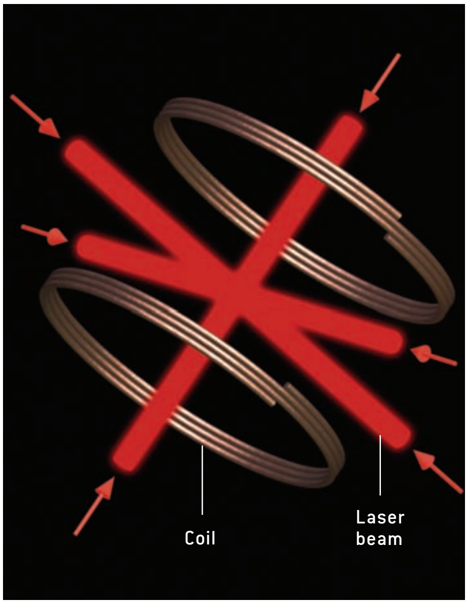
Producing a BEC takes a lot of equipment. The heart of a cold-atom experiment is a small glass box with some coils of wire around it. This cell is completely evacuated, producing in effect a superefficient thermos bottle. Next, a tiny amount of the desired gas is let in. Six laser beams intersect at one point inside the vacuum cell. The laser light need not be intense, so inexpensive diode lasers can often suffice, similar to those found in compact-disc players. At room temperature, the gas atoms irregularly fly through the cell with a speed of several hundred miles per hour. Where they happen to enter into one of the beams, the laser light starts to cool them down very abruptly. Additionally, a weak magnetic field from the wire coils conspires with the laser light to push the atoms toward the intersection of the six beams.

This clever combination of laser light and magnetic field, called a magneto-optical trap (MOT), was devised in 1987 by Jean Dalibard of École Normale Supérieure in Paris. David E. Pritchard of the Massachusetts Institute of Technology and Steven Chu of Stanford University created the first working MOT. Today the MOT is the workhorse of cold-atom physics, cooling gases of rubidium, sodium and many other atomic species to temperatures in the microkelvin range. Yet a MOT achieves only a fairly low density—the atoms are spaced too far apart for their wave functions to overlap. To get higher densities and still lower temperatures at the same time requires another mechanism. This is where evaporative cooling comes into play.

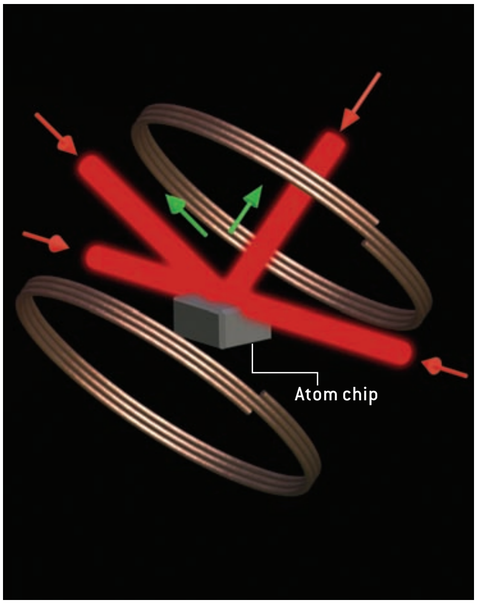
Evaporative cooling works because at every instant some particles in the gas are almost at rest, and others have much more than the average velocity. When those very fast atoms are removed, the remaining gas has a lower temperature. This is not a new idea: it is precisely how a cup of coffee cools when one blows on it.

To apply evaporative cooling to ultracold atoms requires some more refined equipment than a mouth and a pair of lungs, however. In BEC experiments, it is usually performed in a magnetic trap, which can be thought of as a deep bowl with immaterial walls. The most energetic atoms escape from the bowl. The walls of the bowl are steadily lowered so that hot atoms continue to escape, and the cooling process on the remaining ones keeps going.

An essential element of evaporative cooling is that the slower atoms left behind must redistribute their energy—a few of them end up with higher velocities (and are in turn removed from the trap as the evaporation proceeds), whereas the others become even slower and colder. This redistribution occurs through "good" collisions (as distinguished from "bad" collisions with surrounding atoms, which knock the desired atoms out of the trap). This is where the microchip traps weigh in: with small currents, they produce strong fields that compress the atoms more than standard traps, thereby increasing the rate of good collisions. *—J.R.*



In the standard MOT configuration (*left*), six laser beams (*red*) cross in the center of the magnetic field created by two coils. This configuration is difficult to use with a chip—the chip inevitably blocks one or more of the beams.



The solution (*right*) is to apply a mirror coating to the chip and to use only four beams instead of six. Reflection (*green arrows*) from the mirror coating provides the two remaining beams, and cold atoms are collected close to the chip surface.

KENN BROWN

modulated in an appropriate way, a series of potential wells moves across the chip surface. Regulating the currents controls the speed of transport and the distance from the surface. The condensate can be moved and positioned to within a few nanometers, or billionths of a meter. This BEC conveyor belt may become the backbone of more complex devices—for example, in quantum computing, which I discuss below.

But the BEC conveyor is just an initial example. Today researchers have only started to explore the possibilities offered by sculpting the magnetic field.

Magnetic Tubes

WHEN THE CIRCUITRY takes the form of two or three wires running in parallel, the magnetic field forms a tubelike trap along which the atoms can move freely. The magnetic tube is the matter-wave analogue of an optical fiber: a matter waveguide. Light waves in a fiber move along the fiber axis, following its path around curves. Similarly, a condensate moves along a magnetic matter waveguide as a beam of matter. Several research teams have developed such guides (both on microchips and on larger systems) and the techniques for loading atoms into them.

Every atom, like a kind of SCHRÖDINGER'S CAT, must go along BOTH PATHS of the beam splitter at once.

The main application envisaged is atom interferometry. Any kind of interferometry involves combining two waves, resulting in a pattern of high and low amplitudes, or light and darkness. Most interferometry is carried out with laser beams because the technique relies on a property of laser light known as coherence, meaning there is one orderly wave associated with each beam. A traveling BEC is a lot like a laser beam in that it, too, is coherent. Bringing together two coherent atom beams produces interference—a pattern of "bright" spots (lots of atoms) and "dark" spots (with few).

Atom interferometers have evolved over the past decade from proof-of-principle experiments into sensors that compare favorably with other state-of-the-art sensors (although it could be a decade before they make the leap from the laboratory to real-world commercial applications). Most notably, they can be employed to measure rotation, gravity and local variations of gravity—quantities needed for navigation in ships and aircraft. For example, aircraft contain optical-fiber-based interferometers (called laser gyroscopes) to measure rotation—an indispensable supplement to the traditional compass. Gyroscopes based on atom interferometry may be several orders of magnitude more precise.

Important problems with chip-based systems remain to be solved, however. One is the development of coherent beam splitters, which divide a beam of atoms into two beams. A beam splitter is one of the main working parts in any interferometer. For the splitter to be coherent, every atom, like a kind of Schrödinger's cat, must go along both paths of the beam splitter at once—what the splitter does is to divide the atom's quantum wave function in two. In contrast, the chip beam splitters that have been demonstrated so far are more akin to fire hoses: they break apart the beam too abruptly, and each individual atom goes either left or right instead of going both ways at once. These "incoherent" devices cannot be used in an interferometer.

In July 2004 a collaboration between the group of Eric A. Cornell of JILA at the University of Colorado at Boulder and that of Mara Prentiss of Harvard University demonstrated an ingenious laser-based atom interferometer. The researchers created a BEC on an atom chip, and then with a laser pulse they split it into two coherent parts moving away from each other. Additional pulses brought the two parts back together to produce interference.

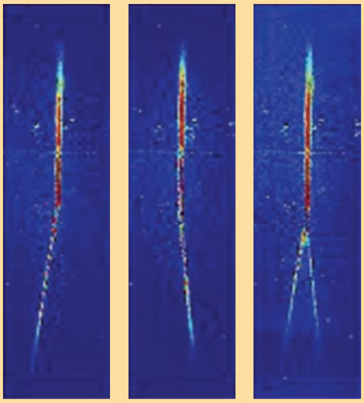
Beam splitters are not the only type of device to exhibit problems with matter waves. In 2002 Zimmermann's group and that of David E. Pritchard (one of the inventors of atom interferometry) at the Massachusetts Institute of Technology saw an unexpected effect when they released a condensate into a waveguide on a chip. Instead of seeing the condensate spread out and fill the guide to its end, like water settling in a long horizontal trough, they saw it start to spread but then stop and split up into fragments [*see box on opposite page*]. These little splashes of matter had been trapped in very shallow corrugations in the magnetic guide.

In March 2004 Alain Aspect and his co-workers at the Institute of Optics in Orsay, France, demonstrated with scanning electron microscopy and elegant analysis that roughness—small deviations of the wires from their ideal, straight form—is the cause of these corrugations in the magnetic waveguide. The tiny bumpiness of the wire is enough to make the current flow in little curves, distorting the magnetic field. These imperfections in the magnetic field have never been measured directly with conventional magnetic field probes. The BEC atoms turned out to be much more sensitive probes.

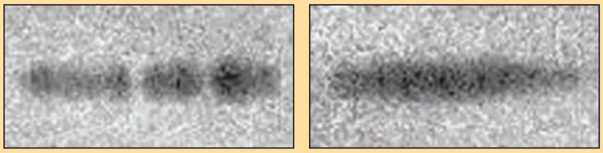
Another problem touches on much more fundamental effects. In experiments carried out so far, the BEC atoms are at least tens of microns from the chip surface. The fascinating quantum character of the atoms would be more pronounced in even smaller traps, but a side effect of making the magnetic traps smaller is that they will hold the atoms that much closer to the chip surface. At these tiny distances—less than one micron—the atoms will inevitably interact with the surface through a process known as the Casimir-Polder force. Indeed, in an experiment carried out in late 2003 by Vladan Vuletic, a young professor at M.I.T., a loss of atoms from the trap was observed when it was

CHALLENGES TO OVERCOME

Matter waves are demanding travelers. If atom chips are to be used in applications, certain problems must be solved.



Incoherence in an atom beam splitter means that each atom goes either left or right where the beam splits. For atom interferometry, researchers are striving to achieve a coherent version where every atom goes left and right simultaneously. At the left, we see an incoherent beam splitter controlling the flow of lithium atoms through its inverted Y shape.



Fragmentation of an atom cloud trapped in the magnetic field of a wire on a chip indicates that the magnetic potential is not completely smooth (*left*). The bumpiness of the magnetic waveguide is caused by microscopic roughness of the wires. When an atom cloud is trapped at exactly the same position but held by a purely optical trap that does not involve the chip wire, no fragmentation appears (*right*).

brought closer than about 1.5 microns to a nonconducting surface.

Finally, another effect that must be dealt with in smaller traps is the thermal magnetism of the chip surface. Imagine a disordered pile of little magnets in constant, chaotic movement. This is what a metal at room temperature looks like at submicron distances. At larger distances, the contributions all average to zero, which is why they have not been seen up until now. When the atoms are brought very close to the surface, however, they once again prove to be extremely sensitive probes. The thermal magnetism causes the magnetic trap to shake and move, and after some time the atoms are washed overboard. The effect was predicted in 1999 by Carsten Henkel of the University of Potsdam—a German theorist who became interested in atom chips soon after they were invented—and was experimentally verified in 2003 by Ed A. Hinds, now at Imperial College London, who had previously trapped cold atoms with other unconventional means such as videotape.

For applications where thermal magnetism is a problem, several solutions exist. The chip can be cooled with liquid nitrogen or even liquid helium, but this requirement complicates the apparatus considerably. As predicted by Henkel and demonstrated in 2003 by Cornell's team, the thermal magnetism is weaker in metals of higher resistivity. Thus, using titanium instead of copper or gold reduces the losses.

Waveguides, and their application in atom interferometers, exploit one particular aspect of the atom's quantum-mechanical nature: its wave character. Other quantum manifestations may lead to other, still more revolutionary applications. Today's star in the quantum scene is the quantum computer [see "Rules for a Complex Quantum World," by Michael A. Nielsen; SCIENTIFIC AMERICAN, November 2002]. This future device would exploit the superposition principle (another peculiar feature of the quantum world) to carry out certain types of computations much faster than any classical computer could do. A quantum computer functions by manipulating qubits, the quantum counterparts to bits. An ordinary, classical (nonquantum) logical bit can only be true or false, 1 or 0. The qubit, by contrast, can be in a superposition state corresponding to any mixture of true and false at the same time, like Schrödinger's cat in its mixture of alive and dead.

In a classical computer, computations corresponding to different bit states must be carried out one after the other. With qubits, they are elegantly performed all at the same time. It has been proven that for certain problems this feature makes a quantum computer fundamentally faster than any classical computer can ever be.

The favorite occupation of quantum physicists these days is to think of practical ways to make a quantum computer: with trapped ions, with large molecules, with electron spins—or maybe with BECs on atom chips. The idea is tempting because such a quantum chip seems so attractively similar to a traditional microelectronics chip and at the same time so radically new. Components such as the atom conveyor could be used to bring qubits together to interact in a controllable fashion.

Thus, the condensate on a chip is the beginning of a story. As so often occurs in science, the plot of the story is not known in advance, and the actors themselves are discovering it in little steps. As in the past, surprises will crop up—pleasant and unpleasant ones. Some obstacles will be removed; others will force researchers to change directions. Whatever we find out will help to bring the classical and quantum worlds still closer together on the stage of science.

MORE TO EXPLORE

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Coherence with Atoms. Mark A. Kasevich in *Science*, Vol. 298, No. 5597, pages 1363–1368; November 15, 2002.

Max Planck Institute of Quantum Optics (Garching) Microtrap Group: **www.mpq.mpg.de/~jar**

University of Heidelberg Atom Chip Group: **www.atomchip.org**

JÖRG SCHMIEDMAYER (*left*); WOLFGANG KETTERLE *Massachusetts Institute of Technology* (*right*)