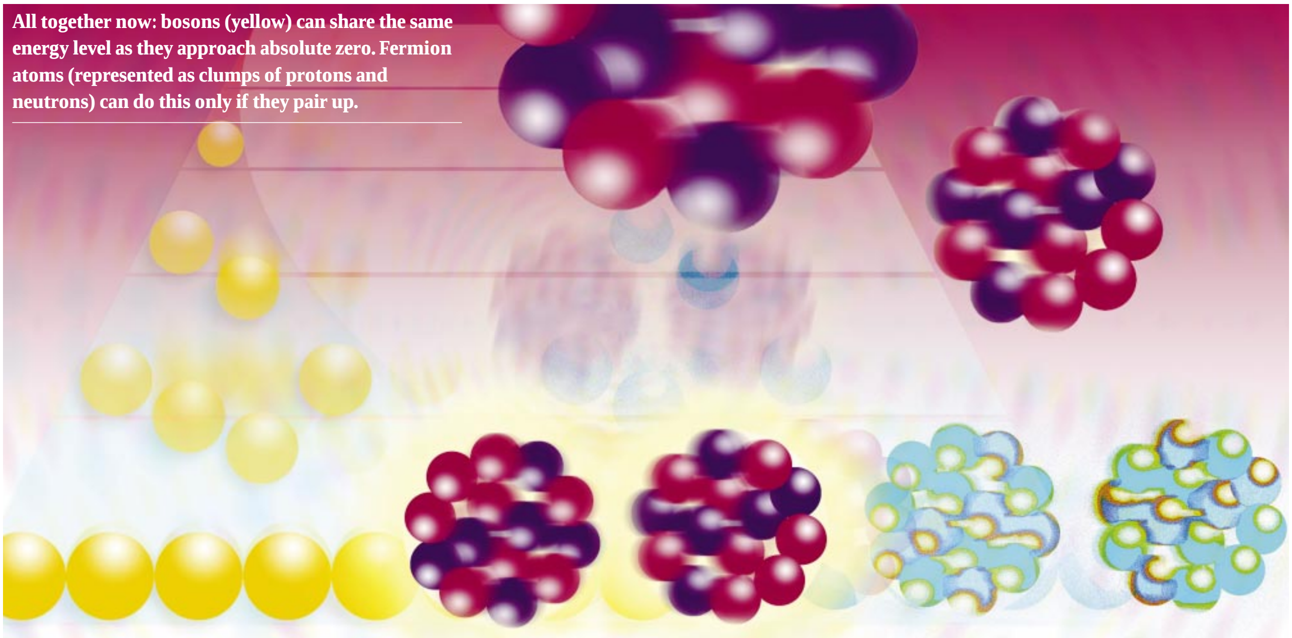


All together now: bosons (yellow) can share the same energy level as they approach absolute zero. Fermion atoms (represented as clumps of protons and neutrons) can do this only if they pair up.

M. XERIDAT

Altered states

During the 1990s, ultracold gases were used to open up a new and often bizarre frontier of physics. Now researchers are poised to use similar gases to enter another, equally intriguing, realm. Mark Haw reports.

Stand by for a new state of matter — according to some predictions, it could be created in the next few months. In a handful of laboratories around the world, physicists are trying to persuade antisocial atoms to pair up to form a new type of 'superatom'.

If they succeed, their creations will have more than curiosity value. The state — called a fermion condensate — would be perfect for testing theories of quantum mechanics, and could even lead to new ways of computing. Those involved in the effort know they are onto something big. "This state is unlike any other," says Murray Holland, a theoretical physicist at the University of Colorado at Boulder, "and we have a physical system in which it may be realized."

The key is to cool gaseous atoms to very low temperatures. An atom's energy is limited to a series of discrete values called energy levels. As a gas reaches very low temperatures, the atoms slot themselves into the few remaining levels above absolute zero.

Different atoms do this in different ways. Those that belong to the boson family of particles, such as atoms whose total number of electrons, neutrons and protons is even, are perfectly comfortable occupying the same energy states as their neighbours. When a gas of bosons is cooled to close to absolute zero, the particles all fall into the lowest energy state.

In quantum mechanics, particles can be represented as waves, and when all the atoms fall into a single energy state, their 'wavefunctions' fit together so that the peaks and troughs match up. The entire gas behaves as a single superatom called a Bose–Einstein condensate (BEC). Such a system was first created in 1995 by Carl Wieman, Eric Cornell and their colleagues at the University of Colorado at Boulder[1].

Antisocial attitudes

Fermions, the family of particles that includes atoms whose total number of particles is odd, are less friendly. Quantum mechanics says that no two fermions can share the same quantum state. As gases of fermions are cooled, the atoms play a game of musical chairs as they compete to secure their own energy level.

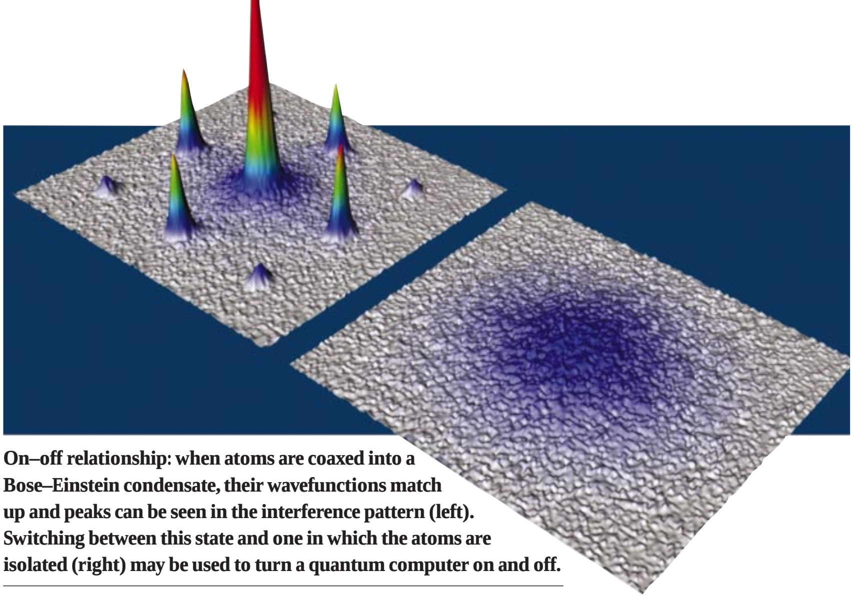
This makes creating a fermion version of a BEC sound impossible. But since the 1950s, physicists have known that, under the right conditions, two fermions can pair up. Take electrons — which are also fermions — in a superconductor. The vibrations of the lattice of atoms through which the electrons move constrains their motion in such a way that the wavefunctions of the individual electrons pair up, and correlations form between them. In terms of quantum mechanics, the electrons form a kind of composite particle, even if they are not spatially close together. At low temperatures, this effect is strong enough for all electrical resistance, which is caused by unpaired electrons, to disappear.

In this case, the electron pairs behave as a single composite boson. So physicists reason that if pairs of fermionic atoms could be paired up in a similar way, they too should act like bosons and, in theory, form fermionic versions of BECs.

This is a tantalizing possibility. BECs have so far been used to test the details of quantum mechanics[2], to model exploding stars[3] and to bring light to a halt[4]. Fermion condensates should open up a whole new range of experiments. And to get the atoms to pair up, physicists are learning how to take direct control of atomic interactions. By doing so, they could find new ways to manipulate matter and explore quantum phenomena.

But getting fermions to pair up in a gas, where there is no atomic lattice to constrain their motion, is a big challenge. The atoms occasionally pair up when they collide. Lowering the temperature, which reduces the speed of the atoms, increases the likelihood

I. BLOCH



On–off relationship: when atoms are coaxed into a Bose–Einstein condensate, their wavefunctions match up and peaks can be seen in the interference pattern (left). Switching between this state and one in which the atoms are isolated (right) may be used to turn a quantum computer on and off.

of pairs forming. But even the ingenious methods used to create BECs, in which the atoms of a gas are cooled by using lasers to slow them down, cannot create temperatures low enough for large numbers of fermion pairs to form.

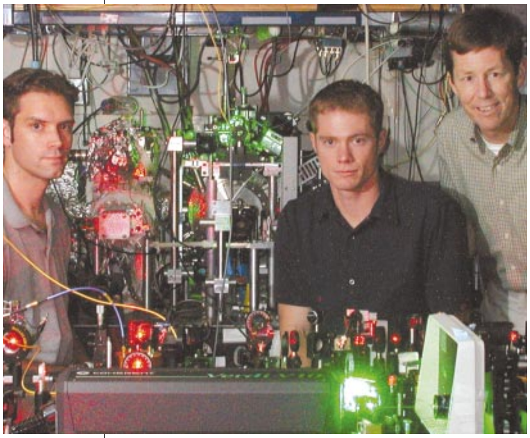
So physicists plan to give the fermions a little push. The favoured method is to use a magnetic field to tweak the energy levels of the electrons orbiting the atoms. Adjusting the levels in the right way increases the chances that collisions will result in pairings.

Take your partners

Last month, Neil Claussen and his colleagues at the University of Colorado used this trick to pair up bosons[5], and the team is now trying to do the same with fermions. Groups led by Wolfgang Ketterle at the Massachusetts Institute of Technology and Randall Hulet at Rice University in Texas are taking similar approaches.

Together with Henk Stoof, a theorist at Utrecht University in the Netherlands, Hulet has calculated that the temperature below which lithium-6 — a fermion — will pair up is close to what can already be achieved by laser cooling[6]. With a little push from an applied magnetic field, it might form a fermion condensate, and Hulet believes his team may be just a few months away from achieving this.

J. FITLOW



Randall Hulet (far right) and his team hope their apparatus will produce a fermion condensate.

But several researchers, including Hulet, remain unsure about whether the theory behind these predictions is correct. With this in mind, Peter Zoller of the University of Innsbruck in Austria and his collaborators have suggested another method for generating a fermion condensate. They propose to use a grid of criss-crossing lasers. At low laser power, the atoms' wavefunctions would be spread out across the whole grid, and at high power, the atoms should be contained within the laser lattice like eggs in an egg-box. But in unpublished work, Zoller's group has shown that, in theory, adjusting the laser power to an intermediate level can cause wavefunctions to match up and atoms to form pairs.

Joint efforts

The creation of a fermion condensate would present quantum physicists with exciting opportunities. Unlike metal superconductors, dilute gases are transparent, so researchers can see into the condensate. Fermion condensates are also interesting because all the fundamental building blocks of matter — from quarks to electrons, protons and neutrons — are fermions. So it might be possible to use atomic fermion condensates to mimic the behaviour of such particles in extreme environments, such as in neutron stars, as well as in less fraught situations, such as electrons in metals.

The condensates will also provide a platform for studying poorly understood aspects of quantum theory. Using quantum mechanics to describe simple systems, such as the hydrogen atom, is relatively straightforward. But for more complex situations, such as interacting molecules, the calculations become fiendishly difficult.

Different approaches to solving these calculations exist, but it is unclear which of these are useful. "The theory is controversial," admits Stoof. "It is not immediately clear what is the correct approach." If they have access to both BECs and fermion condensates, and can tweak atomic interactions using magnetic fields, physicists should be able to test the theory of quantum mechanics as never before. In effect, they will be able to create 'designer gases', tailoring the properties to suit their experiments. "The ability to tune the interactions is the key advantage," says Zoran Hadzibabic, a member of Ketterle's team.

Fermion condensates could also have practical applications, including quantum computing. When the atoms in Zoller's optical egg-box interact, their wavefunctions can combine in many different ways. Quantum mechanics says that the atoms actually exist in a 'superposition' of all these different possibilities until the system is observed. If the atoms could be manipulated in the right way, each different possibility could represent a calculation, allowing the system to perform a large number of calculations in parallel.

This has some potential advantages. One example is finding the factors of very large numbers, a problem at the heart of computer security and some kinds of cryptography. A hypothetical factorization calculation that would occupy a conventional computer for billions of years could be performed in months by a quantum computer.

Zoller predicts that bosons or fermions in his optical egg-box could act as bits of data in a quantum computer if they could be manipulated in the appropriate way. This January, Immanuel Bloch's group at the Max-Planck-Institute for Quantum Optics in Garching, Germany, took a very preliminary step towards this goal by applying Zoller's ideas to bosons[7]. The team placed rubidium atoms in an optical egg-box and, by varying the laser power, managed to toggle the atoms between a BEC — with full quantum behaviour — and a set of isolated atoms. Such a mechanism could be used to switch a quantum calculation on and off.

The theoretical and experimental interest in fermion condensates is surely enough to drive the groups trying to create them onto their goal. But if they need any further motivation, there is also the knowledge that fame may await; after all, those who performed the first experiments with BECs — Wieman, Cornell and Ketterle — won last year's Nobel Prize in Physics. ■

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