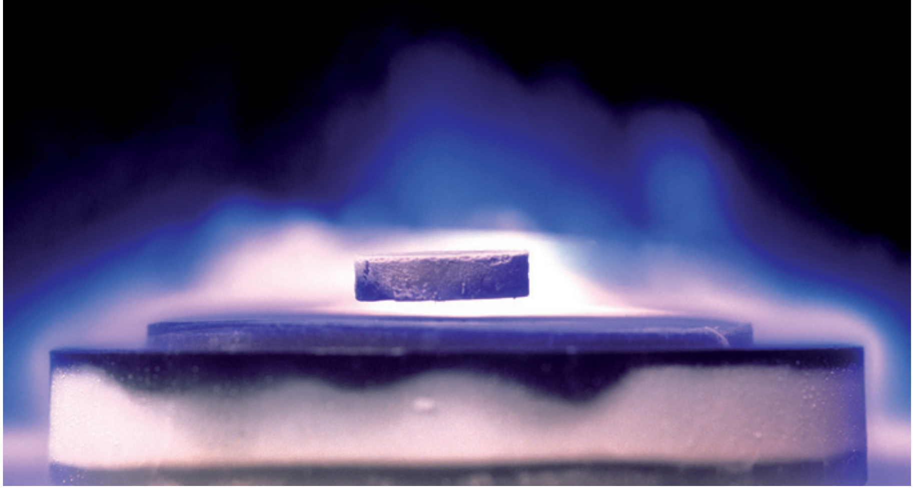
STILL IN SUSPENSE

A quarter of a century after the discovery of high-temperature superconductivity, there is still heated debate about how it works.

BY ADAM MANN



A sample of a high-temperature superconductor hovers in a magnetic field.

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"Even bouncers in New York City nightclubs were aware of our notoriety," says Paul Grant, thinking back to the 1987 March meeting of the American Physical Society (APS).

The hype had been building for months, as newspapers, magazines and morning television talk shows heralded jaw-dropping announcements from physics labs. A technological revolution seemed at hand, promising an era of levitating trains, coin-sized computers and power lines that could span continents without losing energy. When the meeting finally convened, says Grant, a physicist at the energy consulting firm W2AGZ Technologies in San Jose, California, anyone with an APS badge who arrived at a trendy club aptly named 'The Limelight' was ushered straight to the front of the queue.

Yet the public's excitement was nothing compared with the eager frenzy of the physicists. On the evening of Wednesday 18 March, more than 1,800 APS attendees squeezed into a ballroom at the New York City Hilton (while another 2,000 milled outside) to watch a marathon set of presentations that lasted more than 7 hours. At the sometimes-raucous symposium — dubbed the 'Woodstock of physics' — researchers devoured the latest findings on what was easily the most astonishing discovery their field had seen in a generation: materials that became superconductors at high temperatures.

'High-temperature' was a relative term: even the best of the materials would not transition to become superconducting — having no resistance to an electric current — until it was chilled below 93 K (roughly 200 °C below room temperature). But that was nearly four times higher than the transition temperature of any previously observed superconducting material, and shattered what had once seemed to be a solid theoretical upper limit of 30 K. Everyone in the

1911 ▶

A century of superconductivity

Heike Kamerlingh Onnes (seated centre front) and his colleagues discover superconductivity. He receives the Nobel prize in 1913.

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1957

John Bardeen, Leon Cooper and Robert Schrieffer (left to right) publish a theory of superconductivity that predicts a maximum transition temperature of 30 K. They are awarded the Nobel prize in 1972.

1986

Georg Bednorz (left) and Alex Müller find a copper oxide material that becomes superconducting at 35 K.

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ballroom knew that, whatever was going on, it was something profoundly new.

Better still, they knew that 93 K could be achieved easily with cheap, plentiful liquid nitrogen as a coolant, instead of the expensive, tricky-to-handle liquid helium required by the earlier superconductors. Suddenly, applications of superconductivity such as lossless power lines seemed economically feasible. And the room was alive with an even more electrifying idea: could there be materials that superconduct without any refrigeration at all?

But 25 years after the publication of the first paper on high-temperature superconductivity[1], such materials remain a dream. So do most of the miraculous-sounding applications. And so does a deep understanding of what is going on. Despite increasingly refined experimental techniques and nearly 200,000 published papers, physicists still do not have a complete theoretical explanation for high-temperature superconductivity. "It's not that there's no theory; there are lots of theories — just none that most people agree on," says John Tranquada, a physicist at the Brookhaven National Laboratory in Upton, New York.

SLOW PROGRESS

Still, history offers some reassurance. Physicists took 50 years to understand conventional superconductivity — which was discovered 100 years ago in the laboratory of Heike Kamerlingh Onnes, at Leiden University in the Netherlands (see 'A century of superconductivity'). On 8 April 1911, after testing for electrical resistance in a sample of mercury at 3 K, Onnes wrote down "*Kwik nagenoeg nul* (Mercury practically zero)", marking the first observation of a superconductor.

A step towards an explanation of superconductivity came in the 1920s with the development of quantum mechanics, which provided an underlying model for the structure of ordinary metals. Metal atoms form a regular crystalline lattice and hang on to a tightly bound inner core of electrons. But their loosely attached outer electrons become unbound, collecting into a mobile 'electron sea'. Under the influence of an electric field, this ocean of free electrons will drift throughout the lattice, forming the basis of conductivity.

In a normal metal, this motion isn't always predictable: no matter how cold it gets, random thermal fluctuations scatter the electrons, interrupting their forward motion and dissipating energy — thereby producing electrical resistance. But as some metals are cooled to temperatures close to absolute zero, the electrons suddenly shift into a highly ordered state and travel collectively without deviating from their path. Below a critical temperature that is unique to each of these metals, the electrical resistance falls to zero and any current flows practically forever. They become superconductors.

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But why does this ordered state form? In February 1957, three physicists — John Bardeen, Leon Cooper and Robert Schrieffer, all then at the University of Illinois in Urbana-Champaign — published the first complete answer[2].

According to their proposal, now known as BCS theory, an electron moving through a positively charged lattice of atomic nuclei leaves behind a small wake, like the deformation caused by a bowling ball rolling across a mattress. The distortion pulls in another electron, and the two become what is known as a Cooper pair. If many such pairs form, as happens at very low temperatures, their quantum-mechanical wavefunctions align, drawing the pairs into a collective state known as a condensate. Once there, they keep one another in check because breaking up one pair would raise the energies of all the others. The net result is that they all flow together without interruption, creating superconductivity.

The theory was very successful, making many predictions that were quickly confirmed by experiment. But it also implied that the forces binding the Cooper pairs were very feeble, so they would be ripped apart by thermal vibrations at anything other than extremely low temperatures. "Armies of researchers in the 1950s and '60s worked on improving the temperature range," says Jan Zaanen, a theoretical physicist at Leiden University. "But they soon realized that they could not give rise to superconductivity above 25 K or 30 K" — temperatures that generally require elaborate cooling systems for liquid helium, which boils at 4.2 K.

This did not stop the use of superconducting wires and films in certain high-value applications such as medical magnetic resonance imaging (MRI) machines and particle colliders. But the expense seemed to rule out any wider application.

Then, in June 1986, physicists Georg Bednorz and Alex Müller at the IBM Laboratory in Zurich, Switzerland, reported[1] that they had created a material that became superconducting at 35 K. The finding was dramatically confirmed in January 1987, when physicists in the United States found a material in the same class that became superconducting at 93 K (ref. 3). The Woodstock of physics followed barely two months later.

One of the many astonishing aspects of Bednorz and Müller's work was that they were looking not at metals, but at insulating materials called copper oxides, which physicists would soon dub cuprates. In particular, they were investigating what happens when a cuprate is 'doped', or has foreign elements

1987

January: High-temperature superconductivity is confirmed in cuprates, this time at a temperature of 93 K.

March: The American Physical Society hosts the 'Woodstock of physics' (pictured). And Phillip Anderson posits the resonating-valence-bond theory as the mechanism for high-temperature superconductivity.

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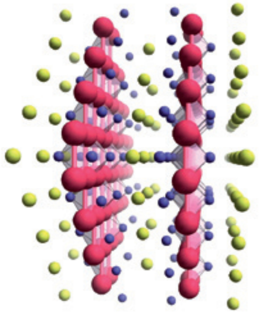
1991

Philippe Monthoux, Alexander Balatsky and David Pines publish the spin fluctuation theory of high-temperature superconductivity.

1993

Researchers discover a material that becomes superconducting at 135 K, setting a world record for the highest transition temperature.

2008



Hideo Hosono and his co-workers discover a new class of superconductors, iron pnictides (pictured).

J. BOBROFF, LPS/ORSAY, FRANCE/WIKIMEDIA

such as lanthanum or barium introduced into the parallel planes of copper and oxygen that comprise its structure. What they found was that the foreign atoms freed up the outer electron of some of the copper atoms, which then flowed through the lattice. If the cuprate was then cooled enough — to a temperature that depended on how it was doped — the electrons would flow freely, and the material would become superconducting.

This strange state of affairs — superconductivity in an insulator — quickly led physicists to re-examine their basic ideas about condensed matter. But because some of the experiments were unknowingly done on impure samples, people were having trouble reproducing the results. “The first years of the field were very confusing,” says Patrick Lee, a physicist at the Massachusetts Institute of Technology in Cambridge. Hypotheses invoking bizarre and exotic physics cropped up, often without much evidence to back them up.

The field soon broke up into competing camps, each advocating a different theory. Researchers would often ignore data that did not jibe with their pet theory, clinging almost religiously to their ideas, and attacking those who believed otherwise.

Kathryn Moler, a physicist at Stanford University in California, recalls a colloquium in which a scientist in the audience stood up, pointed a finger at the speaker and shouted, “Liar! Liar! Ladies and gentlemen, that man is a liar — don’t listen to a word he’s saying!” Igor Mazin, a physicist at the Naval Research Laboratory in Washington DC, remembers a conference in 1989 when physicists promoting the different theories stood on stage “yelling like schoolchildren”.

Eventually, the cacophony sorted itself into the two theories with which most physicists now work. The first, resonating-valence-bond theory[4], is largely the creation of Philip Anderson, a condensed-matter physicist at Princeton University in New Jersey. The theory states that the electron-pairing mechanism is imprinted in the cuprates’ structure. Neighbouring copper atoms can become linked through chemical valence bonds, in which they share electrons with opposite spins. Typically, the bonding locks these spin pairs in place, preventing any current from being carried. But when the material is doped, the pairs become mobile and the valence bonds become Cooper pairs that condense into a superconductor.

The second theory, called spin fluctuation[5], has the most support in the community. Devised by Philippe Monthoux of the University of Edinburgh, UK, Alexander Balatsky from Los Alamos National Laboratory in New Mexico and David Pines from the University of Illinois–Urbana Champaign, it posits that without doping, cuprates are locked into an ordered state called an antiferromagnet. That means that the outer electron on each copper atom lines up such that its spin is opposite to that of its neighbour: one electron will have its spin up, the next down, the next up, and so on. The magnetic fields produced by the spins lock the electrons in place. But in doped cuprates, the foreign atoms break up this rigid chequerboard pattern, giving the spins room to wobble. A passing electron can then set up a pulsating pattern of spins analogous to the lattice distortions of conventional superconductivity. This disturbance then draws moving electrons together, allowing them to associate into Cooper pairs and achieve a superconducting state.

In the early days, says Tranquada, advocates of these two mechanisms were at loggerheads as much as anyone else in this field. But after a while, he says, “it becomes easier to relax a little bit and try to start discussing where the points of agreement are and where the points of disagreement are. We can get beyond opinions and try to make some progress by agreeing on some experiments or calculations that may help.” Most researchers now broadly agree on many aspects, such as the importance of magnetic interaction.

> **“Ladies and gentlemen, that man is a liar — don’t listen to a word he’s saying!”**

Things have also calmed down a bit in the laboratory, as improved techniques have helped researchers to weed out the more exotic theories and refine those that remain. A good example is angle-resolved photoemission spectroscopy (ARPES), a method that uses high-energy photons to probe what electrons are doing. “In 1993, the best we could do was four spectra in 12 hours,” says Zhi-Xun Shen, a physicist at Stanford University who works with ARPES. “One of vastly superior quality now takes 3 seconds.”

And in 2008, Hideo Hosono and his colleagues at the Tokyo Institute of Technology in Japan discovered a second class of high-temperature superconducting material — this time based on iron and arsenic — called pnictides[6]. These materials superconduct at lower temperatures than most cuprates — often only below 40 K— but they have given theorists a new arena for testing their ideas.

“It’s almost like a do-over,” says Thomas Maier, a physicist at Oak Ridge National Laboratory in Tennessee. Pnictides have a more complex structure than cuprates, but they might help to uncover which phenomena are central to high-temperature superconductivity, and which are simply due to the copper oxide structure.

Moreover, finding the pnictides has reassured researchers that they might be able to find other high-temperature superconductors, providing more information or perhaps even a path to the elusive room-temperature superconductor. “Once there’s two, there’s a high probability of there being more,” says Andrew Millis, a physicist at Columbia University in New York.

Researchers have made progress in practical applications. In the past five years, for example, they have managed to string cuprate materials into superconducting tape that can be used in power transmission cables or MRI machines cooled with liquid nitrogen.

THE ROOT OF THE MATTER

No one is predicting a full understanding of high-temperature superconductivity any time soon — not least because such an account would have to make sense of the huge number of papers. “A rich enough theory should explain everything and not just cherry pick,” says David Pines, a physicist from the University of Illinois at Urbana-Champaign.

But it’s not always clear exactly what needs to be explained. Roughly 15 years ago, for example, researchers discovered that some high-temperature superconductors allow electron pairs to form above the transition temperature. In this ‘pseudogap’ regime, the material spontaneously organizes itself into stripes: linear regions that act like rivers and carry electron pairs through the insulating landscape where electrons remain stuck in place. “It’s a precursor state to the superconducting state and is therefore fundamental to understanding this problem,” says Ali Yazdani, a physicist at Princeton University. Not so, says Pines, who thinks the pseudogap state “interferes with superconductivity but is not responsible for it”.

Much as physicists had to wait for highly developed quantum-mechanical tools to unlock the secret behind traditional superconductivity, researchers today may require future ideas to complete their task.

If nothing else, the field’s early quarrels have ensured that only the most determined researchers have stayed. Those remaining are perhaps humbled by their experiences. “I think our biggest problem has been human fallibility,” says Anderson. And perhaps these initial difficulties have helped to forge theories that can stand the test of time. “In the end, it’s your competitor that makes you strong,” says Shen. ■

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