'Warm' superconductors — getting down to tin-tacks

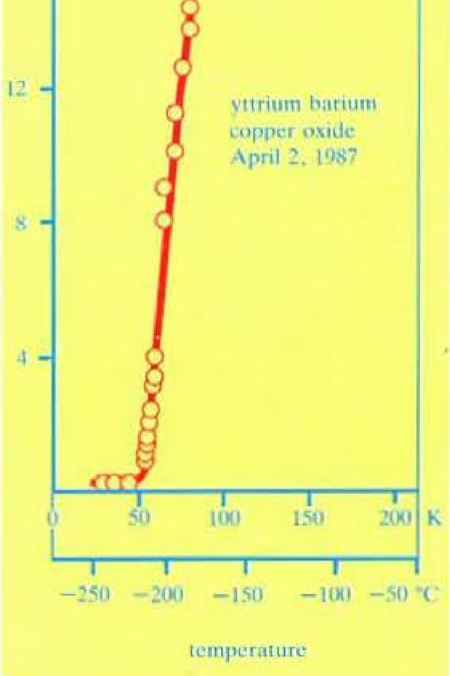
Like magic, a magnet floats serenely in mid air, invisibly suspended above a black grainy disc that sits in a smoking pool of liquid nitrogen.

You are witnessing a startling demonstration of superconductivity. That rough disc is a sample of the new generation of ceramic superconductors, a specially concocted mixture of oxides of rare earth, barium, and copper. Resistance to the flow of electricity completely vanishes after they're chilled with liquid nitrogen.

Levitating magnets are an aspect of the strange world of superconductivity: lines of magnetic force are forbidden to enter the superconductor, causing the repulsion of any nearby magnet (the Meissner effect).

Nobody can give you an adequate explanation of why the new breed of ceramics, which burst upon the scene 2 years ago, become superconductors at temperatures so much higher than previously known materials showing this characteristic.

Superconductivity — discovered in mercury in 1911 — had been largely confined to some metals, and required refrigeration to near absolute zero, a rather involved process requiring liquid helium (boiling point 4 K, or −269°C). The new superconductors operate at temperatures higher than the boiling point of liquid nitrogen (77 K, or −196°C).



No resistance

A historic graph — the resistance of the first 1-2-3 superconductor made by CSIRO dives to zero. Later — improved — samples go superconducting well above liquid-nitrogen temperature (77 K).

The most promising type to date has a 'critical temperature' of about 90 K. At this temperature a sudden transition occurs from partially conducting (above it) to superconducting (below it). This superconductor is a ceramic with a formula close to $YBa_2Cu_3O_7$ (called '1-2-3' because it contains yttrium, barium, and copper in these ratios).

There are now dozens of different superconducting ceramics; the record-holder — one in which thallium replaces the rare earth component — has a critical temperature of 125 K. How soon will it be before materials with even higher transition temperatures are discovered? Is a room-temperature superconductor possible?

Notwithstanding the lack of a theoretical framework, scientists and engineers have seized on the new materials for their perceived potential to bring about dramatic industrial changes with profound social and economic implications.

Possible future applications of superconductors include:

- ▷ zero-loss transmission of electricity along main arteries of the electricity grid (no more high-voltage pylons)
- ▷ super-fast integrated circuits and computers
- ▷ magnetically levitated trains
- ▷ super-powerful electric generators and motors
- ▷ magnetic shielding
- ▷ sensitive scientific and medical instruments
- ▷ high-power magnets for magnetohydrodynamics (by which power could be more efficiently produced than with present rotating generators) and magnetic 'bottles' for nuclear fusion

Australian scientists are caught up in the excitement. When Dr John Macfarlane of the CSIRO Division of Applied Physics read the first report revealing the recipe for the 1-2-3 superconductors, he immediately conferred with his colleagues. Before long, on April 2, 1987, they watched as the temperature of their sample dropped to nitrogen's boiling point and their instruments told them that its electrical resistance was plummeting towards zero.

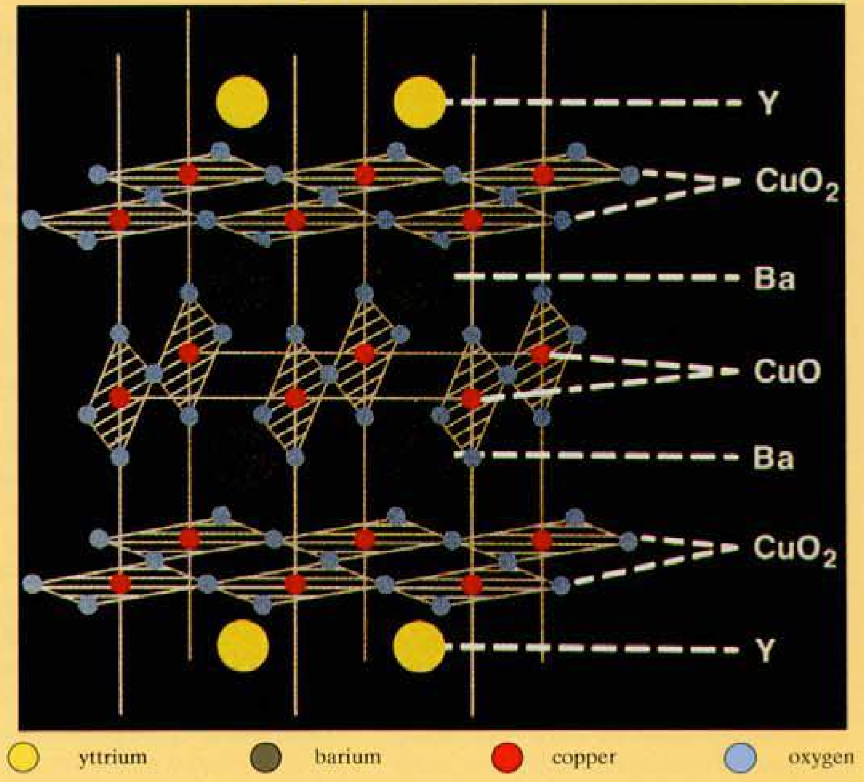
Several groups in CSIRO and Australian universities are undertaking research into ceramic superconductors; collaboration with industry is an important element in the major projects. More than 50 physicists, chemists, electrical engineers, and materials scientists are involved.

Significantly, Australia is endowed with large deposits of rare earths; half the world's supply of one of them, yttrium, comes from this country.

Cool-headed industrialists

The Australian government has awarded four major GIRD grants (Grants for

Superconductor structure



The structure of the '1-2-3' superconductors. A unit cell of $YBa_2Cu_3O_7$ has one atom of yttrium, two of barium, and three of copper. Superconducting electrons travel along the copper–oxygen planes. The desired material is called an oxygen-defect perovskite because oxygen atoms are missing from various locations within the crystal lattice; for best results, O_7 is altered to $O_{6.8–6.9}$.

The science behind the magic

Superconductivity was discovered by the Dutch physicist Heike Kamerlingh-Onnes in 1911. He was astonished to find that when he cooled mercury with liquid helium (a frigid 4 degrees above absolute zero) its resistance completely vanished. An electrical current induced in a ring of mercury would continue indefinitely, a state of affairs impossible for the physics of the day to explain.

It required 46 years of sustained theoretical effort to come up with a satisfactory answer, involving the strange world of quantum mechanics. In 1957, John Bardeen, Leon Cooper, and John Schrieffer offered the world their 'BCS' theory, and it has since become the accepted explanation (it won them a Nobel Prize too).

How can the electrical equivalent of perpetual motion be possible?

In an ordinary conductor, an electron swims in a sea of its confreres. An electrical current is a steady drift of this swarming sea of particles. In their migration, electrons are apt to bump into obstacles — nuclei of the conducting material — and lose energy.

In a superconductor, we have a different situation. In particular, the quantum mechanical 'spin' of the electrons plays a major role. Electrons with spin 'up' are able to pair up with mates that have spin 'down'. Physicists ascribe, as the glue in this arrangement, phonons — quantised vibrations of the nuclei lattice.

Bonded this way, a set of 'Cooper pairs' can overcome collisions with consummate ease. The energy that a lone electron would otherwise lose in such a collision is, in the paired situation, simply transferred to the other electron in the duo and the Cooper pair continues on with undiminished energy.

Satisfying as this BCS theory may be, the unfortunate truth is that it doesn't explain how superconductivity can exist at temperatures much above absolute zero. Thermal agitation should break up the Cooper pairs.

Physicists therefore found it hard to believe the news that Georg Bednorz and Alex Mueller, of IBM in Zurich, had found superconductivity at 36 K in a ceramic — lanthanum barium copper oxide. That was in December 1985, and the hunt for even higher critical temperatures began. (In 1987, the IBM pair won a Nobel Prize for their discovery.)

In March 1987, Dr Paul Chu of the University of Houston, Texas, announced the remarkable 1-2-3 compounds that became superconducting at 80 K.

At least one major feature of the BCS theory can be retained in the new regime: experimentalists agree that electrons still bond into Cooper pairs. But the 'warm' superconductors exceed, by a wide margin, the theoretical temperature limit of phonon-mediated electron coupling. Indeed, some experiments indicate that phonons aren't necessary at these elevated temperatures.

What, then, is the glue? Scientists have picked on quantised virtual particles they call magnons, spinons, modified phonons, holons (and 'and-so-ons'), but no mechanism has stood out as fundamentally it.

Dr Macfarlane points to the likely role of the almost two-dimensional structure of the 1-2-3 crystal. It looks as though copper–oxygen planes are responsible for the superconductivity, and the more such layers are present, the higher the critical temperature becomes. Because conducting layers are separated by insulating layers, a very strong attraction must exist between charge carriers; some unusual mechanism is at play.

Perhaps there is a tie-up here with what happens in other strange superconducting materials that also don't behave in accordance with BCS theory — organic materials, for instance, and uranium compounds that behave as if their electrons were thousands of times more massive than usual.

There's another Nobel Prize waiting for whoever solves the puzzle, but it may take some years yet.

Industrial Research and Development), worth $2 million over 3 years, for superconductor research.

The first, for research into superconducting instruments and sensors, involves the CSIRO Division of Applied Physics, BHP, AWA, and Ausonics. Specific devices to be designed and tested include Josephson junctions and SQUID magnetometers (both superconducting devices that rely on quantum behaviour for extremely sensitive and precise measurements), microbolometers for infrared detection, and magnetic shields for assisting sensitive detectors recover small magnetic signals (such as those produced by the human brain).

Westmead Hospital, Sydney, with help from CSIRO, is presently using a liquid-helium-cooled biomagnetometer, using niobium as superconductor, to investigate the magnetic fields generated by normal and malfunctioning brains; if the instrument can be made to work with liquid nitrogen and ceramic superconductor, costs will fall and a new diagnostic tool may become medically routine.

This instrument, like many others, will rely on tiny sensors formed by depositing thin films of superconductor. The researchers are testing various techniques for preparing such films.

A second GIRD grant, for research on superconducting power cables, also involves the Division of Applied Physics, together with the University of New South Wales (School of Materials Science), ANSTO (the Australian Nuclear Science and Technology Organisation), Metal Manufacturers Ltd, and Elcom (the Electricity Commission of New South Wales).

Metal Manufacturers is a major Australian producer of power cables, and the idea of superconducting cables opens up tremendous possibilities for the company. About 20% of the electrical energy generated at power stations is presently lost as heat in transmission wires. Of course the brittleness of the new ceramic superconductors is a drawback, but the researchers involved in this project have already prepared a length of superconducting wire.

A third grant involves Monash University, Olex Cables, the State Electricity Commission of Victoria, and the CSIRO Division of Materials Science and Technology. These Melbourne-based research teams are looking into the possibilities of using coils of superconductors to store electrical energy as magnetic flux — essentially using the coils as big batteries.

Lastly, the School of Physics at the University of New South Wales is collaborating with AWA in investigating the opportunities for using superconductors in integrated circuits.

Critical factors

While enchantment with the new ceramics is high, we should keep in mind that, at present, they have other problems besides the need for very low temperatures. One, already mentioned, is brittleness; another is poor current-carrying capacity.

The new superconductors are greatly superior to the old in terms of critical temperature, but they lag behind in terms of another parameter, critical current. While the metallic superconductors can carry plenty of current for practical purposes (a million amperes per sq. cm and more), the new materials lose their zero-resistance property under relatively small loads. The best laboratory results so far have been about 100 000 A per sq. cm in single crystals and thin films.

Experiments by Dr Macfarlane and his colleagues confirm that blame lies with the grainy structure. The new material can be seen as comprising superconducting grains weakly coupled together in a composite, with the connections between grains having a wide range of critical currents.

In the 1-2-3 superconductors, current flows easily within grains in two directions, but poorly in the third (see the box). When current must negotiate its way through a jumble of grains, choosing a zero-resistance path is a chancy business.

Recent work by scientists overseas has demonstrated that the restricted capacity of the bulk material can be improved by fusing the grains together at 1300°C and then cooling the material in a special way so as to align the grains in the conducting direction. Using this technique, they have produced bulk samples with critical currents of 17 000 A per sq. cm — several hundred times greater than any previously reported in bulk, and only 10 times short of the critical currents needed for many practical uses.

However, other difficulties have to be solved before large-scale commercial application of the 1-2-3 superconductors is feasible. Since contact with atmospheric oxygen, water, and carbon dioxide downgrades their performance, protection against degradation is a major problem. Also, when a thin film of superconductor is attached to a substrate, atoms from the substrate can diffuse into it and completely destroy its essential properties. Unfortunately, silicon atoms, the basis of modern semiconductor devices, perform this most unwelcome manoeuvre, but intermediate barrier coatings may solve the problem.

A biomagnetometer made by CSIRO can detect the very weak magnetic fields produced by nerve impulses in the brain. This one uses a superconducting detector cooled by liquid helium, but work with 'warm' superconductors could lead to a cheaper liquid-nitrogen-cooled version.

Developing good electrical contacts with this ceramic substance is a bit tricky too. Workers at the University of New South Wales have found that adding a little powdered silver to the sintering mixture makes the contact resistance much smaller.

Given that all these limitations can be overcome one way or another, there will remain one area — electrical noise levels — where the new devices cannot compete with the old. One of the reasons that existing superconducting detectors are so sensitive is that they operate at 4 K. Electrical noise inevitably increases with temperature, and a detector cooled to 4 K will always have a better signal-to-noise ratio than one cooled only to 77 K.

Notwithstanding all the obstacles, the new superconductors offer rich rewards, Dr Macfarlane believes. He thinks Australia has the opportunity to play a significant role in honing and polishing these as-yet rough diamonds. 'We have all the raw materials, a wealth of scientific ability and enthusiasm, and most of the important tools. Will our industry recognise the wonderful potential?'

Andrew Bell