

The pristine voice of electrons

Eminent Canadian physicist, **Dr Louis Taillefer**, explores superconductivity in unconventional materials, with the aim of tuning their properties to realise their full potential. Here, he explains the progress to date, the importance of collaboration and his hopes for the future



Could you begin by defining 'quantum materials'?

We coined the term 'quantum materials' in 2002, to title our Canadian Institute for Advanced Research (CIFAR) programme. Quantum materials exhibit novel magnetic

or electronic properties. Under this label, we include high-temperature superconductors, spin liquids, topological insulators, oxide interfaces with novel functionalities, and even ultra-cold atoms.

Your current research focuses on developing superconductors. What are superconductors and how do they work?

A superconductor is a metal, like aluminium, tin or lead, that undergoes a phase transition below a critical temperature (T_c) into a new state of matter wherein all electrons spontaneously form pairs, called Cooper pairs. Once they form pairs, their properties totally change. The most dramatic, almost magical, property of Cooper pairs is their ability to conduct electricity perfectly, with absolutely zero resistance to current flow: power transmission with zero loss. However, the superconducting state is killed by increasing the temperature above T_c , applying a magnetic field larger than their critical field, or a current larger than their critical current.

Superconductivity was first discovered in 1911. Up to 1986, the maximal value of T_c in all known superconductors was 23 Kelvin (-250 °C), i.e. 23 °C above absolute zero. In 1986, the discovery of superconductivity in copper oxide materials called cuprates increased this maximal value to 164 Kelvin (-109 °C): this is halfway to room temperature (300 Kelvin)!

What are the potential uses of superconductors?

At present superconductors are mostly used as wires to form coils that make

electromagnets to produce large magnetic fields. These superconducting magnets are used in magnetic resonance imaging (MRI) machines in hospitals and in particle accelerators such as the Large Hadron Collider at CERN. And of course to conduct high-field research – we have five superconducting magnets in our lab, producing fields up to 20 Tesla, the largest field in Canada. As for the future, the June 2010 issue of *Scientific American* listed the advent of room-temperature superconductors as one of '12 events that will change everything', along with human cloning, asteroid collision and nuclear warfare! This is because the widespread use of superconductors to transmit electricity on the planet would cause a revolution in the use of green energy.

Why is collaboration so important to your research endeavours?

Research on quantum materials requires three types of experts: the materials experts that synthesise samples and design new materials – the alchemists; the experimentalists that probe their various properties to find out what is going on – the explorers; and the theorists that devise models to explain microscopically what is observed and predict where to look – the philosophers.

CIFAR is a visionary organisation created in 1982 to facilitate, foster, enhance, support and develop this kind of multi-expert collaboration on a global scale. In 1988, CIFAR launched a programme on superconductivity, which became the broader Quantum Materials Program in 2003. It has just been renewed for a sixth five-year mandate, until June 2018.

The programme brings together 60 materials experts, experimentalists and theorists from Canada, the US, France, Germany, Japan, China, Switzerland and the UK – to collaborate on answering big questions in the science of quantum materials. I have had the privilege and honour of being Director of this programme since 1998, and a member since 1992. The resulting strong collaborations have been fundamental to my success in research. Just one of many examples is our collaboration with Proust on high-magnetic field studies of YBCO, using exquisite crystals made by Professors Douglas Bonn and Walter Hardy and Dr Ruixing Liang at the University of British Columbia in Vancouver. We are all CIFAR members. I foresee major advances from this programme in the next five years!

What has been your greatest achievement to date?

My biggest breakthrough was the discovery of quantum oscillations in the cuprate superconductor $\text{YBa}_2\text{Cu}_3\text{O}_y$ called 'YBCO'. Over the previous five years, we had been investigating the behaviour of electrons in YBCO at very low temperature, once superconductivity had been removed by a very large magnetic field – about one million times the Earth's field. These experiments took place at the French National High Field lab, with my colleague and friend Dr Cyril Proust in Toulouse. On 27 February 2007, we noticed some funny wiggles in the resistance versus magnetic field, which upon scratching turned out to be quantum oscillations. Never before observed in a cuprate material, these oscillations are the most pristine voice that electrons have to reveal their nature. The frequency of the oscillations tells us the wavelength of the electrons and the amplitude of the oscillations yield their mass. The wavelength was a complete surprise. Furthermore, the Hall effect revealed that the electrons had a negative charge as opposed to the positive charge expected in these hole-doped materials. These bright new facts caused a change of paradigm, as if the electrons were telling us: 'You've had it all wrong!'

A change of paradigm

Research into novel electronic materials at the **University of Sherbrooke** changed how scientists think about superconductors. Now exploring ways to achieve room-temperature superconductivity, a new frontier may be on the horizon

SUPERCONDUCTIVITY IS A quantum physics phenomenon that allows energy to be transmitted through a material without loss. It occurs when the electrons in that material spontaneously form pairs, upon cooling below a critical temperature (T_c). Large electric currents can be sent through a superconducting wire with no resistance whatsoever. Making coils with such wire can produce huge magnetic fields. Superconducting magnets are used in MRI machines to image the brain and in Maglev trains that levitate and reach speeds in excess of 500 km per hour.

But the widespread and large-scale use of superconductors has been severely limited by the need to maintain the materials at temperatures below -250°C , with the complicated and expensive use of liquid helium. If means were found to develop superconductors capable of operation without the need for elaborate cooling procedures, they could transform computing, electronics and wireless technologies, and be used to deliver electricity in conditions that are at present unthinkable. For example, solar power generated in the Sahara could be transported to Europe safely and efficiently by an underground superconducting cable.

NOT SO HOT

In 1986, the Swiss physicists Georg Bednorz and Alex Müller discovered that some ceramic materials exhibit superconductivity at much higher temperatures than hitherto thought possible – for which they received the Nobel Prize a year later. The materials, copper oxides known as cuprates, can have T_c values as high as 164 K, or -109°C – a huge improvement, but still pretty cold. The nature of the exceptionally strong force that binds electrons

into pairs in the cuprates is still a mystery, although most scientists believe it is fundamentally different from the force at work in the conventional low- T_c superconductors. A popular scenario is that doped cuprates are superconducting for the same reason that undoped cuprates are insulating.

In 2008, the Japanese physicist Hideo Hosono discovered 'high temperature' superconductivity in a completely different class of materials, the so-called 'pnictides', based on iron rather than copper. Here, the most popular scenario is a magnetic one: doped pnictides are superconducting for the same reason that undoped ones are magnetic. The central challenge is to identify those pairing forces and understand in detail how they work and how they might be enhanced, with a view to boosting T_c . The Holy Grail is a room-temperature superconductor – the overarching objective of Louis Taillefer's research, which now centres on the two known families of high-temperature superconductors: the copper-based cuprates and the iron-based pnictides. It is also one of the big questions being tackled by the Canadian Institute for Advanced Research (CIFAR).

CIFAR

"I am an experimentalist – an explorer of matter," states Taillefer, Professor of Physics at the University of Sherbrooke in Canada and Director of CIFAR's Quantum Materials Program. With many years of expertise, Taillefer has received international recognition – and a number of prestigious awards – for his major contributions to experimental research on high-temperature superconductors. He pioneered the use of heat conduction at ultra-low temperatures to determine the symmetry of the

Human ingenuity will find totally unexpected ways to harness the electronic properties of a room-temperature superconductor... there will be fascinating outcomes

superconducting state and to investigate electron behaviour at quantum phase transitions. Taillefer was the first to directly measure the giant electron masses of heavy-fermion metals via quantum oscillations and he discovered the first instance of multiple superconducting phases in one material.

The ambitious vision of the CIFAR programme is to have materials that superconduct at room temperature, support topologically protected excitations, and host a quantum spin liquid. Its approach is to assemble a global network of materials experts, theorists and experimentalists who actively collaborate to explore and understand high-temperature superconductivity, topological protection and magnetic frustration. Because of its collaborative model, grounded in superb materials synthesis, the Quantum Materials Program has emerged as a leader in research on high-temperature superconductors.

THE CRAFTS OF A CONDENSED MATTER PHYSICIST

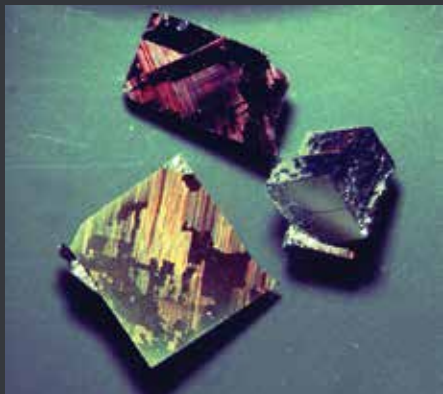
While a doctorate student at the University of Cambridge, working with a compound of uranium and platinum, it became clear to Taillefer that of a breakthrough in superconductivity research lay not only on the judicious selection of materials for experimentation but also on the fabrication of very high quality crystals: "I grew ultraclean single crystals of the heavy-fermion metal UPt_3 and was able to detect quantum oscillations from them: the purest voice of electrons," he enthuses. The electrons in UPt_3 turned out to be the heaviest – and therefore slowest – ever observed, 100 times heavier than those in conventional metals. "There are two aspects to materials synthesis. The first is a search to discover a new superconductor. This is a bit of a black art, modern-day alchemy. The second, which is also a kind of art, is to perfect the quality of the material by growing ultraclean highly-ordered crystals," he notes. "Each new level of perfection opens a new vista of behaviour and discoveries."

Taillefer's team at Sherbrooke includes a research associate, two technicians and students at all stages of their university education – from undergraduates to doctoral students, as well as postdoctoral associates – coming from all over the world. Taillefer finds working with younger scientists highly rewarding: "They are bold and eager. For them the sky is the limit – and they have no preconceived idea of where the sky is supposed to be".

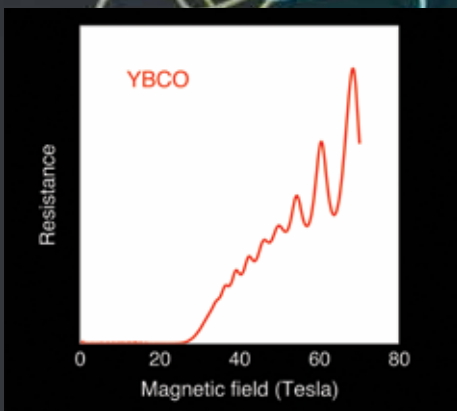
The researchers use a variety of techniques to investigate the behaviour of electrons in matter. They measure electric, thermal and thermoelectric transport properties of materials at very low temperatures, sometimes as low as a few millidegrees above absolute zero. They often apply large magnetic fields, up to 20 Tesla in Sherbrooke or higher when working at national magnet labs such as in Grenoble, France (35 Tesla), in Tallahassee, USA (45 Tesla) or in Toulouse, France (80 Tesla). Recently, they have applied large pressures, up to 30,000 atmospheres, to certain materials. "By squeezing on a material, we can gradually bring the atoms closer, which alters the environment in which the electrons move and in turn modifies their behaviour in a clean and controlled way. For example, the record T_c value in cuprates, 164 K, was obtained by applying pressure to one cuprate material," explains Taillefer.

RECENT DISCOVERIES BY THE TAILLEFER TEAM

In 2007, the group made a key breakthrough in detecting the first quantum oscillations in a cuprate superconductor – oscillations in the resistance of the very best YBCO crystals as a function of magnetic field. This immediately revealed that electrons in cuprates undergo a profound rearrangement. This new trail became a focus of international research, and by 2012 it was clear that a particular form of 'charge order' – or static waves of electron density – are the cause of the electron rearrangement. A new paradigm has thus emerged: rather than the 'insulator scenario' or the 'magnetic scenario' mentioned above, we may have a scenario where



CRYSTALS OF YTTRIUM BARIUM COPPER OXIDE (YBCO), UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER



QUANTUM OSCILLATIONS IN YBCO (LNCMI, TOULOUSE)

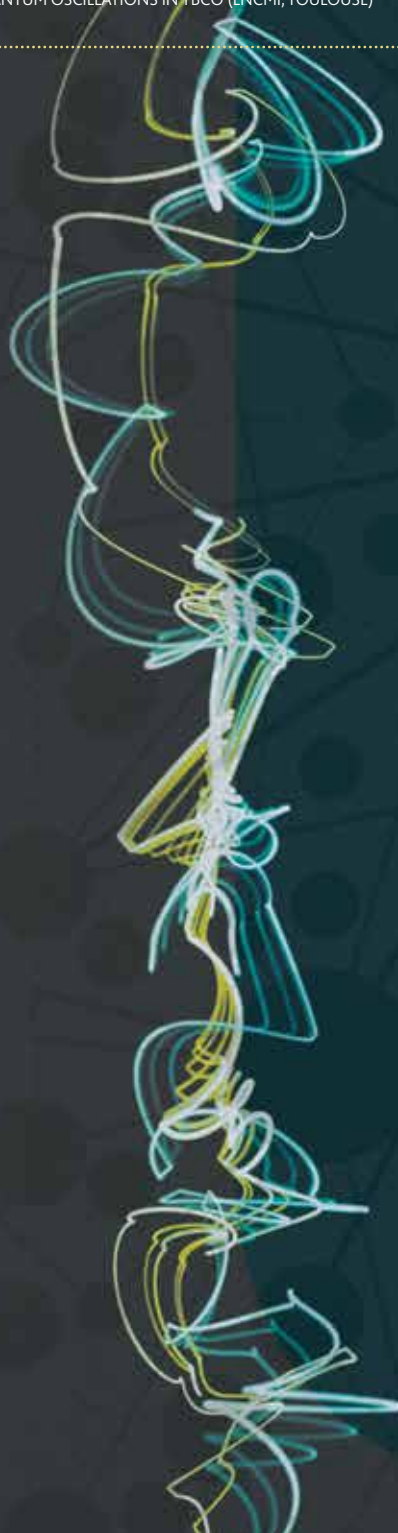
charge order is at the heart of high-temperature superconductivity in cuprates.

In a recent study, Taillefer's team and their collaborators showed that the same electronic rearrangement occurs in another cuprate, with a very different crystal structure, thereby proving that the new phenomena are not specific to YBCO but universal to cuprates. This finding has intensified Taillefer's drive to understand how to tune charge order: "If we can find ways to soften the charge order, or enhance its fluctuations, we may be able to strengthen superconductivity, and raise T_c ."

"In the pnictides, our most recent and thrilling discovery is a change of superconducting state upon applying pressure to KFe_2As_2 ," he explains. There are various types of superconductivity, with different symmetry properties. "Pinning down the symmetry is important because the type of state is a clue to the pairing force responsible for superconductivity and for the magnitude of T_c ."

In all conventional superconductors, like niobium, lead and tin, electrons form s-wave pairs, but in cuprate superconductors, their pairing is of the d-wave type. Because a magnetic force has been shown theoretically to cause comparably stable d-wave and s-wave pairing states in the pnictides, Taillefer now believes that the electrons in KFe_2As_2 go from d-wave pairing at low pressure to s-wave pairing at high pressure, and interprets this as pointing strongly to a binding force of magnetic origin – caused by magnetic fluctuations similar to those that slow down the electrons in UPt_3 . The researchers are currently investigating in detail how this force can be tuned and, ideally, enhanced.

The search to enhance the pairing force and boost superconductivity up to room temperature continues with renewed vigour. A room-temperature superconductor would transform the way electricity is transmitted, and it could enable a green revolution in energy supply. But as happened after transistors were invented in 1947, the greatest impact probably lies in as yet unimagined applications: "My feeling is that when we have a room-temperature superconductor, people's collective ingenuity will find totally unexpected ways to harness the novel properties of its electrons. If thousands of creative individuals play with a superconductor (a macroscopic quantum object!) there will be fascinating outcomes," concludes Taillefer.



INTELLIGENCE

HIGH-TEMPERATURE SUPERCONDUCTORS

OBJECTIVES

- To understand what controls the behaviour of electrons in materials that are the strongest superconductors
- To provide insight into the conditions needed to make a room-temperature superconductor

KEY COLLABORATORS

Dr Nicolas Doiron-Leyraud, University of Sherbrooke, Sherbrooke, Canada

Professor Douglas Bonn; Professor Walter Hardy; Dr Ruixing Liang, University of British Columbia, Vancouver, Canada

Dr Cyril Proust, Laboratoire National des Champs Magnétiques Intenses, Toulouse, France

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LOUIS TAILLEFER is Director of the Quantum Materials Program of the Canadian Institute for Advanced Research. Based at the University of Sherbrooke since 2002, he leads a research group specialised in the experimental investigation of superconductors and other quantum materials at very low temperature and in high magnetic fields.

