AUTHOR COMMENTARIES - From Special Topics

High-Temperature Superconductors - February 2009
Revised: April 2009*
Interview Date: August 2009

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David Cardwell

From the Special Topic of High-Temperature Superconductors

The superconducting materials of interest for engineering applications have a transition temperature, below which they become superconducting, that is at or above 77 K, the boiling point of liquid nitrogen, which is an inexpensive coolant.

According to our Special Topics Analysis of High-Temperature Superconductors over the past decade, the researcher at #15 by total number of papers is Professor David Cardwell, who is credited with 81 papers that have received 414 citations. He is Professor of Superconductivity Research in the Department of Engineering at the University of Cambridge.

In the interview below, ScienceWatch.com's *European correspondent Dr. Simon Mitton converses with Professor Cardwell about his quest for superconducting materials with industrial applications.*

SW: Where did you do your academic training, and what attracted you to research in superconductivity?

I was an undergraduate at the University of Warwick, located in the heart of England. My bachelor degree is in physics, and I remained at Warwick for a Ph.D., on the topic of inelastic gamma-ray scattering (nothing to do with superconductivity!). After that, in 1986, I joined one of the UK's few remaining industrial laboratories (Plessey Caswell, now part of BAE Systems) where "blue skies" research was still encouraged. I set to work on ferroelectric materials, which was somewhat different to the subject area of my Ph.D.

However, within six months of joining Plessey, the first high-temperature superconductor (HTS), a cuprate, was discovered. Plessey had a number of far-sighted individuals who realized the potential of these materials. In view of my recent knowledge of physics and materials science, I was given responsibility for starting research on HTS. Within three weeks I was making my own superconductors, and I never looked back.

SW: Would you like to describe your group in the Department of Engineering at Cambridge?

I established the bulk superconductivity group in 1992 when the department appointed me. Currently we are a modest group by any standards: a couple of post-docs, a couple of doctoral students, and a technician. Our total funding is relatively small: around $300,000 a year.

We've always worked closely with industry and we collaborate extensively throughout Europe and the US. My philosophy is this: the better the people you work with the better the research is going to be. I believe in collaboration, not competition. In 2001 I established an international network spread across 11 European countries. The majority of my papers are about making superconducting materials that can generate large magnetic fields.

Figure 1 [+] details

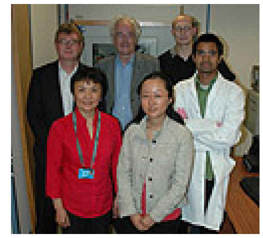

Figure 2 [+] details

SW: Why is that important?

Large magnetic fields are used to provide torque in electrical machines, to enable magnetic suspension, and to improve magnetic resonance imaging. These are examples of applications where the stronger the field, the bigger the torque that can be exerted, or the more stable the magnetic levitation. My group develops materials that can generate large, stable magnetic fields.

SW: So your many HTS papers are devoted to engineering and materials science rather than the fundamental physics of HTS?

While that is correct, this is an area with a large overlap between physics and engineering. One could define engineering as the application of science to practical tasks that are perceived to be useful, whereas physics is the quest to understand the physical world for its own sake. Yes, we have fundamental physics challenges, but in solving those we aim to contribute to developing useful devices as well.

To give an example, we investigate how magnetic flux behaves in materials: in the case of superconductors, the physicists tend to ask about the mechanism of superconductivity, and how high the critical temperature can be pushed, whereas we engineers want to know how high an electrical current the materials can carry, and the highest temperature at which we can get those currents to flow. The current HTS material with the highest superconducting transition temperature is pretty useless at carrying current at a useful temperature!

SW: Why is the development of a viable HTS industry so important?

Superconductivity is the ability of a material to carry an electric current without the dissipation of energy. That is a very topical issue, particularly now given that environmental considerations are so high. Hitherto economic considerations have been driving the technology, but environmental concerns are becoming increasingly important. With superconductivity there are clear potential benefits to the environment. I cannot see any other class of materials even coming close to the potential environmental benefits of HTS.

SW: What examples can you give of environmental benefit?

Up to 20% of the energy can be lost in the transmission electrical energy from a power station to the point of use. If you consider energy storage devices using superconductors, they enable the generated energy to be managed better, enabling its release when and where it is needed. Superconductors allow electrical motors to be made smaller. And guess what? One of the big problems with electrical motors is that large machines cannot be delivered to certain end-user locations in the UK: they are simply too heavy to lift by helicopter, and by road are defeated either by a low bridge or limited road strength.

With superconductors we can invoke an energy density argument: the amount of energy per unit volume is greatly increased, with a corresponding decrease in size and mass for a given quantity of energy. You could potentially use very high-power, high-energy density, compact and lightweight machines virtually anywhere you like by exploiting superconductivity. Superconductors can carry about 100 times more current than copper at 77 K, so if you think about laying superconducting cables it is possible to increase the current-carrying capacity by a factor of 100, although, to be fair, we are still some way off developing practical cables of kilometer lengths.

SW: Considering the HTS materials that are the subject of your highly cited papers, are any of them now being exploited?

Yes. The earliest applications are energy storage flywheels. We have a collaborative program with Boeing in the US, who is developing their own energy storage flywheel using magnetic levitation. I should explain that if you take two dipole permanent magnets, and try to balance north pole over north pole, the top one inevitably flips over in order to minimize energy, by pairing north and south poles. Bulk HTS materials generate the magnetic field in a different way. Unlike permanent magnets, they do not consist of aligned spins. In a superconductor, magnetic field is applied to the sample, which induces a current via Faraday's Law. Removal of the field causes the current to reverse direction, and it continues to flow perpetually in the material. Effectively this is a solenoid without a power supply.

A property of a superconductor is that magnetic flux lines exist in the form of individual filaments within its interior. Furthermore, superconductors contain pinning centers, which prevent or resist the movement of these flux lines. When flux penetrates a superconductor, therefore, it is hard for it to escape. So once you get the magnetic flux into these materials it wants to stay there. And that means superconductors can be used for stable magnetic levitation, and no other materials can achieve that. Bigger trapped flux actually equates to larger currents, so this all ties together quite well.

We are involved in making bulk samples of superconductors for Boeing in the form of specialized geometries, or shapes that can be machined. Our aim is to make large single grains of bulk HTS materials up to several cm in diameter. The point is that grain boundaries limit current flow within the material. Generation of a large magnetic field requires the current to flow over a large area, and therefore we need to replace a large number of micron-sized grains with just one giant grain.

"Hitherto economic considerations have been driving the technology, but environmental concerns are becoming increasingly important."

SW: Five of your top 10 papers in our survey have Dr. Hari Babu as the first author. Can you tell me about that collaboration?

Nadendla Hari Babu was a very successful post-doc in my group for eight years. He joined us in 1998, having pursued a Ph.D. in superconductivity at the University of Hyderabad, India. He now works on advanced solidification technology at Brunel University in West London, but maintains an interest in developing HTS materials for microwave engineering applications with us. We remain close collaborators. He has been my most productive collaborator over the years by some margin, as is reflected in your rankings.

Our joint research focuses on solidification, microstructural, processing, and characterization studies of HTS materials. Among Hari's many achievements are the fabrication of a HTS (NdBCO) with an irreversibility field in excess of 40 T at 77 K, which remains a world record at this temperature, and the development of a practical processing method to fabricate high-performance bulk superconductors. Together we have also successfully developed the technology for fabrication of bulk superconducting nano-composites that are suitable for high magnetic field engineering applications.

SW: What key advance is reported in your highly cited joint paper, "Processing and microstructure of single grain, uranium-doped Y-Ba-Cu-O superconductor" (Babu NH, *et al., Supercond. Sci. Tech*. 15[1]: 104-10, January 2002)?

We describe doping a YBCO superconductor with uranium dioxide to enhance flux pinning. That paper reports the processing, microstructural features, and magnetic properties of large-grain YBCO doped with, in this case, depleted uranium. We succeeded in enhancing pinning for reasons that were not immediately obvious. When we looked in detail at the material microstructure, however, we found the presence of unique secondary phase inclusions that have some remarkable properties that we have subsequently patented. This phase has the potential to revolutionize the generation of high magnetic fields by bulk HTS. It's a phase that retains its integrity when added to the melt process: it does not get bigger, it does not react, and, most importantly, the properties of the HTS are not changed. The phase is about the size of a magnetic flux line so it pins very well. As I have already said, the better the magnetic flux is pinned (nailed down!) the better the current-carrying capability of the material. #1 reports a doubling of the current, just by introducing this phase.

SW: What for you is the unifying thread to the papers in this Special Topics analysis?

All of these papers are about processing and properties. They report detailed understanding of the processing of rare earth barium copper oxides in the form of large grains. For example, phase diagrams show the effect of certain parameters on processing, which determine fundamentally the integrity of the materials we produce, their electrical, magnetic, and mechanical properties, and provide insight into how we can process materials with better properties

SW: Finally, Professor Cardwell, what are your priorities right now?

Our goals are to continue to produce good materials but to do so in a practical way that can be scaled up from laboratory demonstrations to industrial production. That means developing batch-processing methods for the manufacture of samples with uniform properties; samples that are better, bigger, cheaper, and more reliable.

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KEYWORDS: HIGH-TEMPERATURE SUPERCONDUCTORS, BULK SUPERCONDUCTIVITY, LARGE STABLE MAGNETIC FIELDS, TORQUE, ENVIRONMENTAL BENEFITS, ELECTRICAL ENERGY, ELECTRICAL MOTORS, CURRENT, APPLICATIONS, ENERGY STORAGE FLYWHEELS, YBCO, NDBCO, MAGNETIC FLUX.

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Figures and descriptions:

Figure 1:

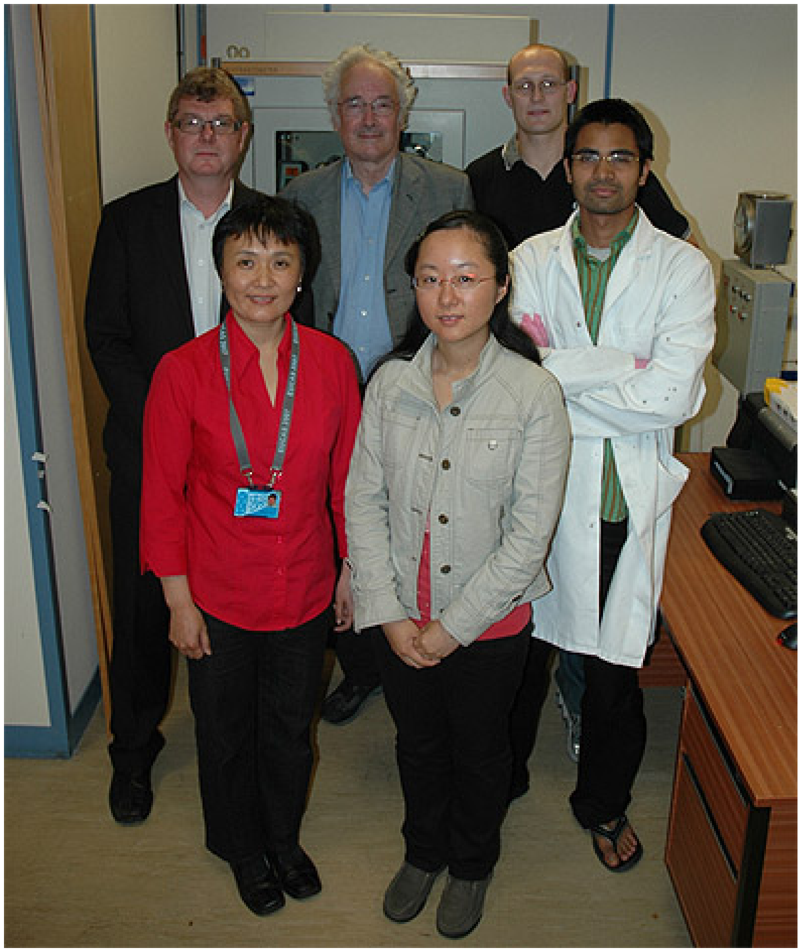

Figure 1:

Pictured (left to right): back; David Cardwell, Archie Campbell, Tony Dennis. Front; Yun-Hua Shi, Zhihan Xu, Sandeep Pathak.

Figure 2:

Figure 2:

A bulk single grain sample of superconducting Y-Ba-Cu-O being levitated by a permanent magnet.

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