interview

SQUIDs for everything

John Clarke told *Nature Materials* about his work on superconducting quantum interference devices — SQUIDs — and his fascination with their applicability to many fields, from medicine to geophysics to quantum information and cosmology.

When did you start working on superconductivity?
It was during my PhD project. I joined the Cavendish Laboratory at Cambridge University as a research student in 1964 and my advisor was Brian Pippard, one of the best-known scientists in the field of superconductivity. My initial project was to measure the electrical resistance of the boundary between a superconductor and a normal metal, which is related to the way in which electrons incident on the boundary from the normal side convert to Cooper pairs, which carry a supercurrent.

How was this related to Josephson junctions and SQUIDs?
My project required me to develop an extremely sensitive voltmeter, able to detect one picovolt. This was very challenging, but a seminar given by Brian Josephson in the department in November 1964 gave us the essential idea. Brian talked about the quantization of magnetic flux in a superconducting loop, and about Cooper pairs tunnelling from one superconductor to another through an insulating barrier — known to everyone else as the Josephson effect. These were the ingredients for the d.c. SQUID, which had just been invented at the Ford Motor Laboratory. The SQUID consisted of two Josephson junctions connected in parallel on a superconducting loop. The maximum supercurrent the SQUID could sustain oscillated with an applied magnetic field with a period given by the flux quantum. I was utterly fascinated, and I was very excited when the next day Brian Pippard walked into my lab to tell me that he had figured out how (by using a SQUID) we could achieve an even better voltmeter than we needed. His idea was simply to couple a superconducting coil inductively to a SQUID loop. A current passed through the coil would produce oscillations in critical current of the SQUID. Connecting a resistor in series with the coil would create a voltmeter, which according to simple calculations should have a sensitivity of two femtovolts in one second. I can safely say this was the turning point in my career: it dictated the direction of research that I have followed for nearly five decades.

© PEG SKORPINSKI

Was it easy to make a SQUID back then?
Not really. Superconducting device technology was quite primitive, and I found it difficult to make stable SQUIDs. The solution was serendipitous, as it often is. My colleague Paul Wraight suggested that as niobium wire, which is a superconductor, is coated with an oxide layer, if we put a blob of PbSn solder, which is also a superconductor, on it, we would create a Josephson junction. Despite my scepticism we tried it right away — and it worked! After a few weeks I had a voltmeter with a sensitivity of ten femtovolts in one second. We had only to give it a name, and this was easy, because Brian Pippard's first reaction was that it looked like a slug. And thus the SLUG — superconducting low-inductance undulatory galvanometer — was born.

Subsequently you moved from Cambridge to the University of California, Berkeley, but you always worked with SQUIDs. What makes them so fascinating to you?
The SQUID is a basic, incredibly sensitive technology that allows one to reach out to many fields. Over the years I have worked on fundamental problems in superconductivity, but I have also been involved in applications to geophysics, nuclear magnetic resonance (NMR), nondestructive evaluation, magnetocardiography and — at present — medicine, cosmology and particle physics.

Which branch of medicine exactly?
Magnetic resonance imaging (MRI), though not the conventional kind. Clinical MRI, which acquires images of the body from the NMR of protons at about 64 MHz, is the single most-important application of superconductivity. There are perhaps 30,000 MRI machines worldwide. I suspect that few people lying in one of these machines realize that they are surrounded by about 50 km of superconducting wire immersed in liquid helium. It is an extremely important clinical instrument. However, there are some things it's not so good at, for example distinguishing tumour tissue from healthy tissue. This is because at 64 MHz the difference in the longitudinal relaxation times of tumour and healthy tissues is difficult to detect. In 2001 Robert McDermott, Alex Pines, Andreas Trabesinger and I began a project to study NMR at frequencies as low as a few tens of hertz using SQUID detection of the signal. At these very low frequencies SQUIDs are much more sensitive than conventional detection coils. These experiments turned out to be quite successful, and subsequently we built an ultralow frequency (ULF) MRI machine operating at 5.6 kHz — four orders of magnitude lower than a conventional MRI machine. It turns out that at these low frequencies the contrast in the relaxation times of different tissues is significantly enhanced. My colleagues Sarah Busch and Paul SanGiorgio are about to complete a study comparing the relaxation times of tumour and healthy tissue in *ex vivo* prostate specimens that have been surgically removed at the University of California, San Francisco. We find that the relaxation time in healthy tissue is about 50% higher than in tumour tissue. This difference should be sufficient to allow us to image prostate cancer in patients. Hopefully, we will complete a prototype clinical system to make preliminary *in vivo* studies of prostate cancer next year.

Are there other medical applications, outside your own work?
One that has been quite successful is magnetoencephalography. Typically, 300 SQUID detectors are arranged in a fibreglass helmet containing liquid helium, which is placed around the patient's head to monitor

the tiny low-frequency magnetic signals generated by the firing of neurons in the brain. This can be used, for example, for presurgical mapping of brain tumours. Various visual, audio and tactile stimuli are applied to map out the brain function in the area around the tumour, enabling the surgeon to minimize the collateral brain damage resulting from the removal of the tumour. Other applications include locating the sites of focal epilepsy and monitoring the recovery of brain function following brain trauma or stroke.

■ From medicine to cosmology: where is the connection?

The essential point is that SQUIDs are extremely sensitive detectors of magnetic and electric signals from any origin. One of today's most fascinating questions is the nature of the cold dark matter (CDM), which constitutes 22% of our universe. A likely candidate is the axion, a very light particle first proposed to explain the absence of any observable electric dipole moment of the neutron — and hitherto not observed. In the mid-1990s, a group at Lawrence Livermore National Laboratory constructed ADMX (Axion Dark Matter eXperiment). It consists of an electromagnetic cavity immersed in liquid helium and surrounded by a 7 T magnet. Putative axions in the cavity decay into photons, which are detected by an antenna connected to a cooled, low-noise semiconductor amplifier. To detect the photons, their frequency has to be in resonance with the cavity, and because the mass of the axion is unknown so is the photon wavelength; hence the cavity length has to be tuned. With the noise of a semiconductor amplifier it would take centuries to scan over one decade of frequency. One day Leslie Rosenberg and Karl van Bibber came to visit and asked me if it were possible to build a low-noise SQUID amplifier operating in the GHz range. At the time this was quite a challenge, but with Michael Mück and others we made such an amplifier which, when cooled to millikelvin temperatures, is essentially quantum-limited, that is, its performance is limited by the uncertainty principle. With the cavity also at millikelvin temperatures, ADMX should now take a few months to scan one decade. The SQUID amplifier has been successfully tested on ADMX at 2 K, and the Department of Energy has funded the upgrade to cool the cavity and SQUID to 50 mK. Thus, in a few years ADMX will be able to make a definitive search for the axion. This is a good example of how a SQUID can make an impractical experiment extremely viable.

■ All these SQUIDs are based on low-temperature superconductors. Wouldn't it be advantageous to use cuprate superconductors working, for example, at liquid-nitrogen temperature, 77 K?

Well, of course when high-transition-temperature (T_c) superconductors were discovered my group and many others tried to make SQUIDs from them. We made magnetometers, gradiometers and voltmeters that worked pretty well. There are two main problems, however, that prevent their widespread application. One is simply that the noise energy of a SQUID scales with the absolute temperature, so that SQUIDs are quieter at 4 K than at 77 K. The other is that — despite some excellent work at the University of Twente and elsewhere — we do not have a Josephson-junction technology as reproducible as that achieved with conventional superconductors, notably the Nb–AlOx–Nb structures pioneered by John Rowell and co-workers.

■ Is anisotropy a problem as well?

Indeed it is. The very high reproducibility of SQUIDs involving planar Nb–AlOx–Nb junctions enables the fabrication of thousands of SQUIDs on a silicon wafer. The in-plane layered nature of the cuprates implies that if electrons have to tunnel perpendicularly between two films via an insulating barrier the coupling is extremely weak. Rather, the junction should be made in the plane of the film, which is a much more challenging proposition. It is possible, however, that junctions based on the newly discovered Fe-based superconductors may be more successful, because the anisotropy in these materials is much lower than in the cuprates.

■ So no real applications for high-T_c SQUIDs so far?

Well, that's not quite true. One highly successful application is a geophysical survey tool developed by a team led by Cathy Foley at CSIRO, Sydney and used, for example, to detect conductive ore. In this technique, a large electrical current is induced in the ground by a powerful generator. As this current decays, the magnetic field it produces — which is strongly dependent on the subsurface electrical conductivity — is detected by high-T_c SQUIDs. From these magnetic fields it is possible to infer the subsurface conductivity. Using SQUIDs allows detection down to very low frequencies where the sensitivity of conventional coils becomes very poor. In remote areas it is quite costly and cumbersome to carry along the liquid helium required for low-T_c SQUIDs. Using high-T_c SQUIDs, on the other hand, enables the use of liquid nitrogen, which is much easier to transport, in a small, lightweight portable dewar. This technique is used by several companies, and it is reported that they have found mineral deposits worth billions of dollars.

■ Is there any material-science issue that could be addressed to improve the performance of low-T_c SQUIDs?

As I mentioned, the junction technology for low-T_c superconductors is rather robust. Nevertheless something needs be done to improve the performance of superconducting quantum bits, for example the flux qubit. This is similar to a SQUID except that it contains three Josephson junctions. A circulating supercurrent in the loop of the flux qubit produces a magnetic flux that can point either up or down, just like the spin of a single electron. The up and down flux states can be superposed to form a macroscopic, coherent quantum state. As well as demonstrating a beautiful piece of physics, the flux qubit is a contender for the building block of a future quantum computer.

Both SQUIDs and flux qubits suffer from flux $1/f$ noise, that is, a noise power that increases inversely with frequency, f. This noise is very detrimental to qubits, because it leads to strong decoherence. Recently, SangKook Choi, Dung-Hai Lee, Steve Louie and I showed that disorder at the interface of the superconductor and the substrate causes electrons to localize. These localized electrons randomly flip their spins, producing magnetic flux noise. This year, Steve Anton, Jeff Birenbaum, Andrew Fefferman, Sean O'Kelley and I showed that these electrons seem to be highly correlated. The community is now trying to reduce this noise by growing the superconductor epitaxially to improve the interface morphology.

■ You will certainly keep working on SQUIDs for years to come. In which field will you concentrate your efforts?

I am deeply committed to ULF-MRI and ADMX, which are long-term projects. I would be thrilled to see ULF-MRI used in the clinic, for example, to image cancer, and to see ADMX undertake a viable search for the axion. It turns out that ADMX can also be used to search for exotic particles such as the chameleon and paraphoton. I have been trying to understand flux $1/f$ noise for 30 years(!), and am determined finally to do so. Beyond these projects I have long been intrigued by the quantum behaviour of macroscopic circuits and making quantum-limited measurements with SQUIDs. For example, Emile Hoskinson, Jed Johnson, Chris Macklin, Irfan Siddiqi and I used a SQUID to read out a flux qubit with a tiny fraction of a photon. I think it will ultimately be possible to use a SQUID to detect the magnetic moment of a single electron.

INTERVIEW BY FABIO PULIZZI