SUPERCONDUCTING ELECTRONICS

The nanoSQUID makes its debut

A superconducting quantum interference device made with carbon nanotubes may be able to measure changes in the magnetic moment of a single molecule.

Marco Aprili
is at the Laboratoire de Physique des Solides, Université Paris-Sud, 91405 Orsay, France.
e-mail: aprili@lps.u-psud.fr

Interferometers come in all shapes and sizes. The laser-based systems built to detect gravitational waves stretch to several kilometres, whereas radio astronomers use dishes that can be thousands of kilometres apart. At the other end of the scale, some 12 orders of magnitude smaller, physicists in France have now made a superconducting quantum interference device (SQUID) from a single-walled carbon nanotube just one nanometre in diameter[1].

In general, interferometers work by splitting a wave into two components, sending them off along different paths, and then recombining them to record an interference pattern. This allows us to measure any phase differences between the two components of the wave that arise from differences in their path lengths or the conditions along their paths. For example, two water waves emanating from the same point will stay in phase if they travel the same distance, but will fall out of phase if one of them has to deviate around an obstruction. Measuring the phase difference between the two waves then provides information about the obstruction.

The same principle applies to the quantum interferometer designed by Jean-Pierre Cleuziou, Wolfgang Wernsdorfer and co-workers[1]. In their device, a superconducting loop is formed from thin aluminium wires, which superconduct below 1.2 K. In a superconductor, the electrons form Cooper pairs with one spin-up electron and one spin-down electron. The superposition of all of the Cooper pairs is a quantum state described by one macroscopic wavefunction. In the device described by Cleuziou (Fig. 1), the superconducting wavefunction splits and travels along the arms of the loop as a zero-resistance current[1]. Importantly, the loop is broken up by two sections of the same carbon nanotube that act as obstructions to the wave.

The device shown in Fig. 1 has the basic structure of all SQUIDs, which turn out to be very sensitive magnetic-field detectors. So, how does a SQUID actually detect magnetic field? One of the quantum features of a superconducting loop is that the magnetic flux, Φ, passing through it — which is the product of the magnetic field and the area of the loop — is quantized in units of $\Phi_0 = h/(2e)$, where h is Planck's constant, $2e$ is the charge of the Cooper pair of electrons, and Φ_0 has a value of 2×10^{-15} tesla m^2. If there are no obstacles in the loop, then the superconducting current will compensate for the presence of an arbitrary magnetic field so that the total flux through the loop (due to the external field plus the field generated by the current) is a multiple of Φ_0.

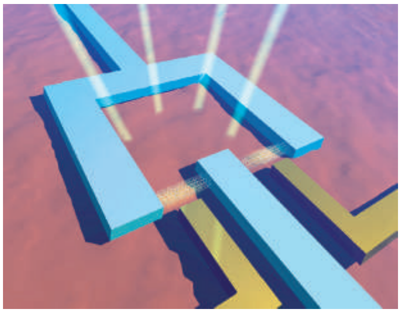
In 1962, Josephson predicted that a superconducting current can be sustained in the loop, even if its path is interrupted by an insulating barrier[2] or a normal metal. However, the insulating barrier will introduce a phase shift to the wavefunction depending on the magnitude of the current through it.

The SQUID in Fig. 1 has two such barriers or 'Josephson junctions'. Both junctions introduce the same phase difference when the magnetic flux through the loop is 0, Φ_0, $2\Phi_0$ and so on, which results in constructive interference, and they introduce opposite phase difference when the flux is $\Phi_0/2$, $3\Phi_0/2$ and so on, which leads to destructive interference. This interference causes the critical current density, which is the maximum current that the device can carry without dissipation, to vary as $|\cos(\pi\Phi/\Phi_0)|$ — an effect that was first observed[3] in 1964.

The critical current is so sensitive to the magnetic flux through the superconducting loop that even tiny magnetic moments can be measured. The critical current is usually obtained by measuring the voltage drop across the junction as a function of the total current through the device. Commercial SQUIDs transform the modulation in the critical current to a voltage modulation, which is much easier to measure. With appropriate read-out electronics, such SQUIDs have a white noise of a few $10^{-6}\Phi_0$ Hz$^{-1/2}$ (ref. 4). SQUIDs have been fabricated to perform fundamental tests of quantum mechanics[5,6], and also to make extremely sensitive magnetic-field detectors for applications as diverse as medicine and geology.

But even the most sensitive SQUIDs face a challenge when it comes to

a



b

Figure 1 The nanoSQUID. **a**, An artist's impression and **b**, an atomic force microscopy image of the SQUID built by Cleuziou and co-workers[1]. In **b**, the grey regions are the aluminium superconducting paths, the thin vertical line is the carbon nanotube — two segments of which form the Josephson junctions — and the yellow regions are the gate electrodes by which a voltage is applied to each nanotube junction. The superconducting current comes in from the right, separates along the two arms of the loop, passes through the nanotube junctions and recombines at the left. The gate voltages applied to the two carbon nanotube junctions control the flow of electrons from the superconducting leads through the nanotubes. The magnetic field lines (four vertical lines) that pass through the loop are shown only in **a**.

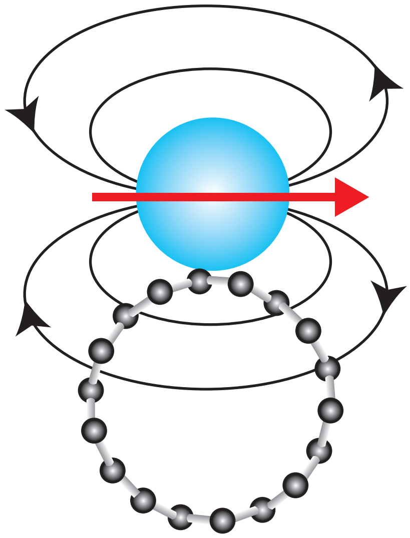


Figure 2 In the magnetization measurements suggested by Cleziou *et al.* the magnetic nanoparticle (blue) is placed directly on the carbon nanotube Josephson junction (grey). When the dimensions of the nanoparticle and the junction are similar, the coupling between the magnetic flux of the particle (black lines) and the loop formed by the nanotube and the aluminium (see Fig. 1) is optimized. If the junction is much larger than the nanoparticle, very little of the magnetic field passes through the loop.

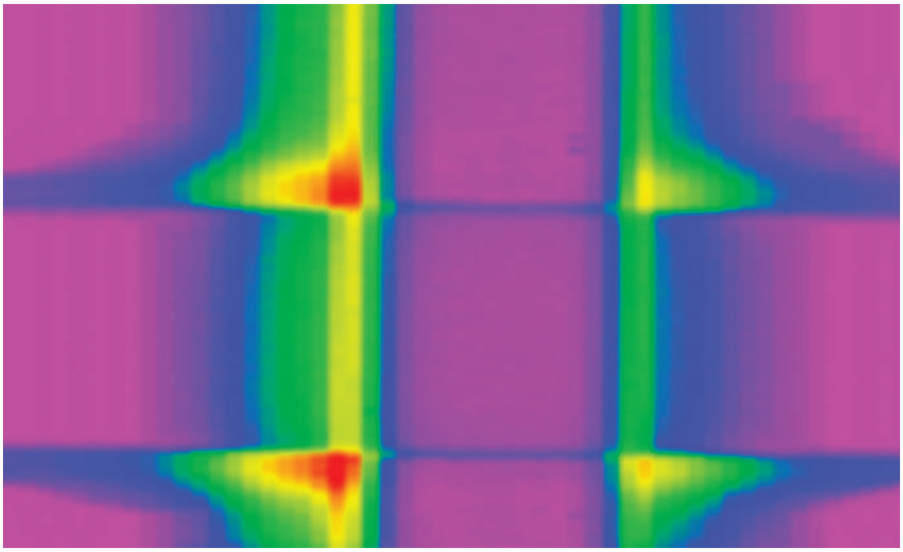


Figure 3 The maximum switching current of the nanoSQUID measured as a function of the voltages at the two gates shown in Fig. 1 (*x* and *y* axes). The colour scale runs from 0 (purple) to 0.4 nA (red).

measuring the magnetic properties of nano-sized particles. In the measurement technique typically used to measure small magnetic particles with microSQUIDs, the particle is placed directly on one of the SQUID junctions. However, when the particle dimensions are much smaller than those of the junction, relatively little of the particle's magnetic field penetrates the SQUID loop.

The nanotube SQUID described by Cleuziou and co-authors[1] is a milestone in nanomagnetism because it could eventually allow the magnetization reversal of individual magnetic molecules to be measured. How? The nanotube diameter is about 1 nm, which is comparable to the dimensions of a typical magnetic molecule. As a result, nearly half of the magnetic flux generated by a single magnetic molecule placed on the nanotube would go through the SQUID loop, resulting in nearly optimized magnetic flux coupling (Fig. 2). This flux coupling is thus greatly improved in a nanotube SQUID compared with one entirely fabricated by state-of-the-art nanolithography techniques, for which the cross-section of the Josephson junction is at least two orders of magnitude bigger. Cleuziou and co-authors estimate that with further optimization of their setup, they could have sufficient sensitivity to measure the magnetization reversal associated with a single Mn_{12} molecule[1].

Interest in nanoSQUIDs will go well beyond technology and applications. In fact, these devices provide new insights into the Josephson coupling between the superconducting arms when the junction is a quantum dot with well-separated electronic energy levels. The nanotube acts as a quantum dot because the electronic wavefunctions in the nanotube are confined by the insulating contacts with the superconducting leads. Applying a voltage to a nearby metal 'gate' changes the number of electrons on the nanotube. When the number of electrons on the nanotube quantum dot is odd, the tube behaves as a magnetic impurity which can interact with the spin of an electron as it tunnels from one superconducting lead to the other[7]. As in a field-effect transistor, where the current from the source to the drain depends on the voltage of the gate, here the gate voltage tunes the superconducting current through the loop. In this sense, the nanotube SQUID also functions as a Josephson transistor[1,8].

One of the remarkable effects that Cleuziou *et al.* demonstrate is that the direction of the superconducting current depends on whether there are an even or odd number of electrons on the nanotube. When this number is odd, the superconducting phase across the tube is shifted by π (ref. 8). Where does this π phase shift come from? When a Cooper pair crosses a quantum dot occupied by an odd number of electrons, the spins of both electrons in the pair are flipped. From a mathematical standpoint, this is the same as changing the sign on the superconducting wavefunction or, equivalently, the sign of the superconducting current. By measuring the interaction between the spin on the dot and the conducting electrons, the experiment reported by Cleuziou *et al.* points out the role of the spin degree of freedom in quantum interference[1].

The nanotube SQUID allows us to explore two important problems in physics. We can use the SQUID as a magnetometer to measure the total spin of a magnetic molecule and understand its dependence on field. We can also observe the π phase shift in the superconducting current produced by the spin of a single electron sitting in the nanotube. In two quite different ways, one familiar, the other more subtle, the nanoSQUID allows us to 'count' spins.

REFERENCES

1. Cleuziou, J.-P., Wernsdorfer, W., Bouchiat, V., Ondarçuhu, T. & Monthioux, M. *Nature Nanotech.* **1,** 53–59 (2006).
2. Josephson, B. D. *Phys. Lett.* **1,** 251–253 (1962).
3. Jaklevic, R. C., Lambe, J., Silver, A. H. & Mercereau, J. E. *Phys. Rev. Lett.* **12,** 159 (1964).
4. Weinstock, H. (ed.) *SQUID Sensors: Fundamentals, Fabrication and Applications* (Kluwer Academic, Dordrecht, The Netherlands, 1996).
5. Leggett, A.J. *J. Phys.* **14,** R415–R451 (1988).
6. Chiorescu, I., Nakamura, Y., Harmans, C. J. P. M. & Mooij, J. E. *Science*, **299,** 1869–1871(2003).
7. Kouwenhoven, L. & Glazman, L. *Phys. World* **14,** 33–38 (January 2001).
8. Jarillo-Herrero, P., van Dam, J. A. & Kouwenhoven, L. P. *Nature* **439,** 953–956 (2006).