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SCIENCE

The Discovery of Tunneling Supercurrents

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The events leading to the discovery of tunneling supercurrents took place while I was working as a research student at the Royal Society Mond Laboratory, Cambridge, under the supervision of Professor Brian Pippard. During my second year as a research student, in 1961–1962, we were fortunate to have as a visitor to the laboratory Professor Phil Anderson, who has made numerous contributions to the subject of tunneling supercurrents, including a number of unpublished results derived independently of myself. His lecture course at Cambridge introduced the new concept of "broken symmetry" in superconductors (*1*), which was already inherent in his 1958 pseudospin formulation of superconductivity theory (*2*), which I shall now describe.

As discussed by Cooper in his Nobel lecture last year (*3*), according to the Bardeen-Cooper-Schrieffer (BCS) theory there is a strong positive correlation in a superconductor between the occupation of two electron states of equal and opposite momentum and spin. Anderson showed that in the idealized case where the correlation is perfect the system can be represented by a set of interacting "pseudospins," with one pseudospin for each pair of electron states. The situation in which both states are unoccupied is represented by a pseudospin in the positive z direction, whereas occupation of both states is represented by a pseudospin in the negative z direction; other pseudospin orientations correspond to a superposition of the two possibilities.

The effective Hamiltonian for the system is given by

$$\mathcal{H} = -2 \sum_{k} (\epsilon_k - \mu)\, s_{kz} - \sum_{k \neq k'} V_{kk'}\, (s_{kx}\, s_{k'x} + s_{ky}\, s_{k'y}) \qquad (1)$$

the first term being the kinetic energy and the second term the interaction energy. In this equation s_{kx}, s_{ky}, and s_{kz} are the three components of the kth pseudospin; ϵ_k is the single-particle kinetic energy; μ is the chemical potential; and $V_{kk'}$ is the matrix element for the scattering of a pair of electrons of equal and opposite momentum and spin. The kth pseudospin sees an effective field

$$\mathbf{H}_k = 2(\epsilon_k - \mu)\, \hat{\mathbf{z}} + 2 \sum_{k \neq k'} V_{kk'}\, \mathbf{s}_{k'\perp} \qquad (2)$$

where $\hat{\mathbf{z}}$ is a unit vector in the z direction and $\perp$ indicates the component of the pseudospin in the xy plane.

One possible configuration of pseudospins consistent with Eq. 2 is shown in Fig. 1a. All the pseudospins lie in the positive or negative z direction, and the direction reverses as one goes through the Fermi surface since $\epsilon_k - \mu$ changes sign there. If the interaction is attractive, however (corresponding to negative $V_{kk'}$), a configuration of lower energy exists, in which the pseudospins are tilted out of the negative direction into a plane containing the z axis, and the pseudospin direction changes continuously as one goes through the Fermi surface, as in Fig. 1b.

The ground state of Fig. 1b breaks the symmetry of the pseudospin Hamiltonian (Eq. 1) with respect to rotation about the z axis, which is itself a consequence of the conservation of the number of electrons in the original Hamiltonian. Because of this symmetry, a degenerate set of ground states exists in which the pseudospins can lie in any plane through the z axis. The angle ϕ which this plane makes with the $0xz$ plane will play an important role in what follows. Anderson made the observation that, with a suitable interpretation of the Gor'kov theory (*4*), ϕ is also the phase of the complex quantity F which occurs in that theory.

I was fascinated by the idea of broken symmetry and wondered whether there could be any way of observing it experimentally. The existence of the original symmetry implies that the absolute phase angle ϕ would be unobservable, but the possibility of observing phase differences between the F functions in two separate superconductors was not ruled out. However, consideration of the number-phase uncertainty relation suggested that the phase difference $\Delta\phi$ could be observed only if the two superconductors were able to exchange electrons. When I learnt of observations suggesting that a supercurrent could flow through a sufficiently thin normal region between two superconductors (*5*), I realized that such a supercurrent should be a function of $\Delta\phi$. I could see in principle how to calculate the supercurrent but considered the calculation to be too difficult to be worth attempting.

I then learnt of the tunneling experiments of Giaever (*6*), described in the preceding lecture (*7*). Pippard (*8*) had considered the possibility that a Cooper pair could tunnel through an insulating barrier such as that which Giaever

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used but argued that the probability of two electrons tunneling simultaneously would be very small, so that any effects might be unobservable. This plausible argument is now known not to be valid. However, in view of it, I turned my attention to a different possibility, that the *normal* currents through the barrier might be modified by the phase difference. An argument in favor of the existence of such an effect was the fact that matrix elements for processes in a superconductor are modified from those for the corresponding processes in a normal metal by the so-called coherence factors (*3*), which are in turn dependent on $\Delta\phi$ (through the u_k's and v_k's of the BCS theory). At this time there was no theory available to permit a calculation of the tunneling current, apart from the heuristic formula of Giaever (*6*), which was in agreement with experiment but could not be derived from basic theory. I was able, however, to make a qualitative prediction concerning the time dependence of the current. Gor'kov (*4*) had noted that the F function in his theory should be time-dependent, being proportional to $e^{-2i\mu t/\hbar}$, where $h = 2\pi\hbar$ is Planck's constant and μ is the chemical potential as before (*9*). The phase ϕ should thus obey the relation

$$\partial\phi/\partial t = -2\mu/\hbar \qquad (3)$$

whereas in a two-superconductor system the phase difference obeys the relation

$$\frac{\partial}{\partial t}(\Delta\phi) = 2\,e\,V/\hbar \qquad (4)$$

where e is the electronic charge and V is the potential difference between the two superconducting regions, so that

$$\Delta\phi = 2\,e\,V\,t/\hbar + \text{const.} \qquad (5)$$

Since nothing changes physically if $\Delta\phi$ is changed by a multiple of 2π, I was led to expect a periodically varying current at a frequency $2eV/h$.

The problem of how to calculate the barrier current was resolved when one day Anderson showed me a preprint he had just received from Chicago (*10*), in which Cohen, Falicov, and Phillips calculated the current I flowing in a superconductor–barrier–normal metal system, confirming Giaever's formula. They introduced a new and very simple way to calculate the barrier current—they simply used conservation of charge to equate it to the time derivative of the amount of charge on one side of the barrier. They evaluated this time derivative by perturbation theory,

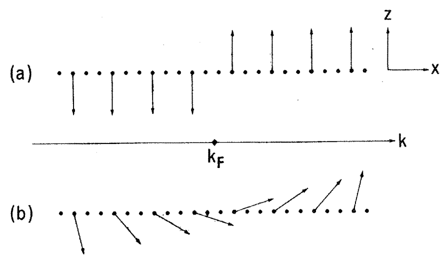

Fig. 1. Pseudospin configurations in (a) a normal metal and (b) a superconductor; k_F is the Fermi momentum.

treating the tunneling of electrons through the barrier as a perturbation on a system consisting of two isolated subsystems between which tunneling does not take place.

I immediately set to work to extend the calculation to a situation in which both sides of the barrier were superconducting. The expression obtained was of the form

$$I = I_0(V) + I_1'(V)\cos(\Delta\phi) + I_1(V)\sin(\Delta\phi) \qquad (6)$$

At finite voltages the linear increase with time of $\Delta\phi$ implies that the only contribution to the d-c current comes from the first term, which is the same as Giaever's prediction, thus extending the results of Cohen *et al.* to the two-superconductor case. The second term had a form consistent with my expectations of a $\Delta\phi$ dependence of the current due to tunneling of quasi-particles. The third term, however, was completely unexpected, as the coefficient $I_1(V)$, unlike $I_0(V)$ and $I_1'(V)$, was an *even* function of V and would not be expected to vanish when V was put equal to zero. The $\Delta\phi$-dependent current at zero voltage had the obvious interpretation of a supercurrent, but, in view of the qualitative argument mentioned earlier, I had not expected a contribution to appear of the same order of magnitude as the quasi-particle current, and it was some days before I was able to convince myself that I had not made an error in the calculation.

Since $\sin(\Delta\phi)$ can take any value from -1 to $+1$, the theory predicted a value of the critical supercurrent of $I_1(0)$. At a finite voltage V an "a-c supercurrent" of amplitude $\{[I_1(V)]^2 + [I_1'(V)]^2\}^{1/2}$ and frequency $2eV/h$ was expected. As mentioned earlier, the only contribution to the d-c current in this situation ($V \neq 0$) comes from the $I_0(V)$ term, so that a two-section, current-voltage relation of the form indicated in Fig. 2 is expected.

I next considered the effect of superimposing an oscillatory voltage at frequency ν onto a steady voltage V. By assuming that the effect of the oscillatory voltage would be to modulate the frequency of the a-c supercurrent, I concluded that constant-voltage steps would appear at voltages V for which the frequency of the unmodulated a-c supercurrent was an integral multiple of ν, that is, when $V = nh\nu/2e$ for some integer n.

The embarrassing feature of the theory at this point was that the effects predicted were too large! The magnitude of the predicted supercurrent was proportional to the normal state conductivity of the barrier, and of the same order of magnitude as the jump in current occurring as the voltage passes through that value at which production of pairs of quasi-particles becomes possible. Examination of the literature showed that possibly d-c supercurrents of this magnitude had been observed, for example, in the first published observation of tunneling between two evaporated-film superconductors by Nicol, Shapiro, and Smith (*11*) (Fig. 3). Giaever (*12*) had made a similar observation but ascribed the supercurrents seen to conduction through metallic shorts through the barrier layer. As supercurrents were not always seen, it seemed that the explanation in terms of shorts might be the correct one, and the whole theory might have been of mathematical interest only (as was indeed suggested in the literature soon after).

Then, a few days later, Phil Anderson walked in with an explanation for the missing supercurrents, which was sufficiently convincing for me to decide to go ahead and publish my calculation (*13*), although it turned out later not to have been the correct explanation. He pointed out that my relation between the critical supercurrent and the normal state resistivity depended on the assumption of time-reversal symmetry, which would be violated if a magnetic field were present. I was able to calculate the magnitude of the effect by using the Ginzburg-Landau theory to find the effect of the field on the phase of the F functions, and concluded that the earth's field could have a drastic effect on the supercurrents.

Brian Pippard then suggested that I should try to observe tunneling supercurrents myself, by measuring the characteristics of a junction in a compensated field. The result was negative—a current less than a thousandth of the predicted critical current was suf-

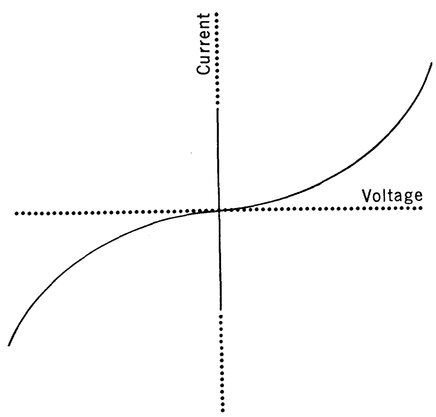

Fig. 2. Predicted two-part current-voltage characteristic of a superconducting tunnel junction.

ficient to produce a detectable voltage across the junction. This experiment was at one time to be written up in a chapter of my thesis entitled "Two Unsuccessful Experiments in Electron Tunneling between Superconductors."

Eventually Anderson realized that the reason for the nonobservation of d-c supercurrents in some specimens was that electrical noise transmitted down the measuring leads to the specimen could be sufficient in high-resistance specimens to produce a current exceeding the critical current. With John Rowell he made some low-resistance specimens and soon obtained convincing evidence (*14*) for the existence of tunneling supercurrents, shown particularly by the sensitivity to magnetic fields, which would not be present in the case of conduction through a metallic short. In one specimen they found a critical current of 0.30 milliampere in the earth's magnetic field. When the field was compensated, the critical current increased by more than a factor of 2, to 0.65 milliampere, whereas a field of 2 millitesla was sufficient to destroy the zero-voltage supercurrents completely. Later Rowell (*15*) investigated the field dependence of the critical current in detail and obtained results related to the diffraction pattern of a single slit, a connection first suggested by J. C. Phillips (*16*). This work was advanced by Jaklevic, Lambe, Silver, and Mercereau (*17*), who connected two junctions in parallel and were able to observe the analog of the Young's slit interference experiment. The sensitivity of the critical current to the applied magnetic field can be increased by increasing the area enclosed between the two branches of the circuit, and Zimmerman and Silver (*18*) were able to achieve a sensitivity of 10^{-13} tesla.

Indirect evidence for the a-c supercurrents came soon after. Shapiro (*19*) shone microwaves onto a junction and observed the predicted appearance of steps in the current-voltage characteristics. The voltages at which the steps occurred changed as the frequency of the microwaves was changed, in the manner expected. In 1966, Langenberg, Parker, and Taylor (*20*) measured the ratio of voltage to frequency to 60 parts per 10^6 and found agreement with the value of $h/2e$ then accepted. Later they increased their accuracy sufficiently to be able to discover errors in the previously accepted values of the fundamental constants and derive more accurate estimates (*21*), thus carrying to fruition an early suggestion of Pippard (*22*). The a-c supercurrent is now used to compare voltages in different standards laboratories without the necessity for the interchange of banks of standard cells. If two laboratories irradiate specimens with radiation of the same frequency, constant-voltage steps appear at identical voltages. The intercomparison of frequencies can be carried out in a straightforward manner by transmission of radio signals.

At the end of 1963, the evidence for the existence of the a-c supercurrent was only indirect. John Adkins and I tried to observe the effect by coupling together two junctions by a short (~ 0.2-millimeter) thin-film transmission line. The idea was that radiation emitted by one junction would modify the characteristics of the other. The experiment, planned to form the second part of the thesis chapter referred to above, was unsuccessful, for reasons which are still unclear. Later, Giaever (*23*) was able to observe the a-c supercurrent by a method similar to the one we had considered, and then Yanson, Svistunov, and Dmitrenko (*24*) succeeded in observing radiation emitted by the a-c supercurrent with a conventional detector.

Finally, I should like to describe the SLUG (superconducting low-inductance undulatory galvanometer) (*25*), developed in the Royal Society Mond Laboratory by John Clarke while he was a research student. Clarke was attempting to make a high-sensitivity galvanometer using the previously described magnetic interferometers with two junctions connected in parallel. One day Paul Wraight, who shared a room with Clarke, observed that the fact that one cannot solder niobium using ordinary solder must mean that, if one allows a molten blob of solder to solidify in contact with

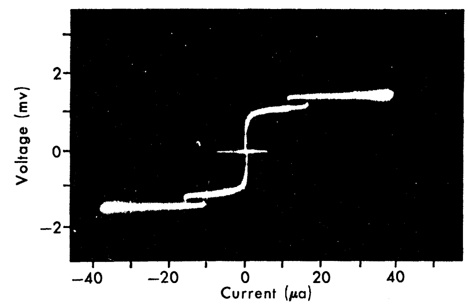

Fig. 3. The first published observation of tunneling between two evaporated-film superconductors (*11*). A zero-voltage supercurrent is clearly visible. It was not until the experiments of Anderson and Rowell (*14*) that such supercurrents could be definitely ascribed to the tunneling process.

niobium, there must be an intermediate layer of oxide, which might have a suitable thickness to act as a tunneling barrier. This proved to be the case. However, in Clarke's specimens, in which a niobium wire was completely surrounded by a blob of solder, the critical current through the barrier proved to be completely insensitive to the externally applied magnetic fields. It was, however, found to be sensitive to the magnetic field produced by passing a current through the central wire. This fact led to the development of a galvanometer with sensitivity of 10^{-14} volt at a time constant of 1 second.

There have been many other developments which I have not had time to describe here. I should like to conclude by saying how fascinating it has been for me to watch over the years the many developments in laboratories over the world, which followed from asking one simple question, namely, what is the physical significance of broken symmetry in superconductors?

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to be $\mathcal{H} - \mu N$. Transition to a situation where the time dependence is given by the true Hamiltonian $\mathcal{H}$ can be accomplished by means of a gauge transformation, and consideration of the effect of this transformation on the electron operators gives immediately Gor'kov's result $F \propto \exp(-2\, i\, \mu\, t/\hbar)$.
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Cortical Control of Cell Division

The cell surface appears to determine some specific events of division in *Stentor* and egg cells.

Noël de Terra

Recently, evidence has accumulated in support of the hypothesis that the surface membrane of animal cells plays an important part in the regulation of cell division. Much of this evidence has come from work on three systems: the ciliate *Stentor*, egg cells, and mammalian cells in culture. When the results obtained from work on these three cell types are considered together, they complement each other in a very interesting way. The work on *Stentor* has provided direct experimental evidence that cell surface changes are involved in timing the cell cycle, regulating some major events of organelle replication, and effecting cytokinesis; it has not yet yielded information about the biochemical nature of these changes. By contrast, the work on cultured cells has shown the existence of specific biochemical surface changes associated with progress through the cell cycle (*1*) or with neoplastic transformation (*2*), but has not demonstrated that these changes are involved in regulating any specific events of cell division. The work on egg cells serves as a bridge connecting the work on *Stentor* with that on cultured cells because it has suggested that the cell surface regulates some specific events of cell division in mitotically dividing cells as well as in the amitotic divisions of ciliates. In this article I review the work on *Stentor* and egg cells and show how the data from these systems complement and reinforce the conclusions arising from work on cultured cells. A broader view of the problem is thus obtained by examining it simultaneously from these different vantage points.

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Cortical Control in Stentor

The interphase cell. *Stentor coeruleus* (Fig. 1) is a trumpet-shaped ciliate which can extend to a length of about 1 millimeter. Its large size and exceptional powers of wound healing have made it a favorable experimental organism for work involving cell microsurgery. The anteriorly located oral apparatus contains a band of oral membranelles (fused plates of cilia originating from rows of basal bodies). This band encloses a circle of cortex (the frontal field) which spirals into a gullet. About 100 rows of blue-green pigment granules run longitudinally down the body. These are graded in width and the widest and narrowest stripes meet on the ventral surface to form the "locus of stripe contrast" (*3*). The pigmented stripes alternate with clear stripes containing the somatic kineties (ciliary rows); these are longitudinal rows of paired basal bodies from which originate cilia and various fibrillar structures. The subcortically located chain macronucleus spirals almost the entire length of the cell. About 40 to 60 tiny diploid micronuclei are scattered along the macronuclear chain.

The cortex of *Stentor* consists of (i) a surface membrane continuous over both the cell body and the ciliary axonemes, and (ii) various structures situated beneath this membrane to a depth of 3 to 5 micrometers. Most prominent among these are the kinetosomes together with the various microtubule systems originating from them (that is, ciliary axonemes, K_m fibers) and the microfilamentous M-bands or myonemes.

Cell division in Stentor. Most major events of cell division in *Stentor* are events of organelle replication. Indeed, the first sign of division (Fig. 2) is the assembly of basal bodies at the locus of stripe contrast; these form the oral primordium which gives rise to the feeding structures of the posterior daughter cell. These newly formed basal bodies sprout cilia and align themselves in rows to form the oral membranelles. The developing membranellar band lengthens and curves, and the posterior end then invaginates to form a gullet. The oral apparatus migrates upward to its final position as the cleavage furrow separates the two daughter cells.

During division, the chain macronucleus undergoes a sequence of morphological transformations (coalescence, elongation, nodulation). These changes double the number of macronuclear nodes, thus preserving the nuclear chain which is presumably advantageous in terms of increased surface area. The diploid micronuclei undergo mitosis while these macronuclear changes are taking place.