About eight years ago a 22-year-old student
showed his professor some calculations on quantum tunneling.
Now that professor tells us

How Josephson discovered his effect

Philip W. Anderson

The discovery of what we have ever since called the "Josephson effect" took place while I was visiting Cambridge, England, for a sabbatical year in 1961-62. Recently, when I travelled to Kyoto to accept the London Prize on Brian Josephson's behalf, I put together some reminiscences of that period, which may be more interesting than a mere recapitulation of the bare scientific facts. Lest I appear too central to this account, I should make it clear that at least two other people could have told a similar story from their own points of view. They are Brian Pippard, Josephson's thesis advisor while the work was being done, and David Shoenberg, director at that time of the Mond Laboratory in which Josephson was a research student in experimental physics and where I served as nominal head of the solid-state theory group.

The discovery

Josephson had taken my course on solid-state and many-body theory. This was a disconcerting experience for a lecturer, I can assure you, because everything had to be right or he would come up and explain it to me after class. Probably because of the course and some of the things I said, he showed me his calculations within a day or two after first making them. At first he followed directly some recent calculations, by Morrel Cohen, Leo Falicov and James Phillips,[1] of the current by the "tunneling Hamiltonian" method, applied to two superconductors separated by an insulating layer. But by the time I saw the calculations he had already worked out the rather sophisticated formalism he later published in which he kept track of particle charges.

By this time I knew Josephson well enough that I would have accepted anything else he said on faith. However, he himself seemed dubious, so I spent an evening checking one of the terms that make up the current. We were all-Josephson, Pippard and myself, as well as various other people who also habitually sat at the Mond tea table and participated in the discussions of the next few weeks-very much puzzled by the meaning of the fact that the current depends on the phase. (This is the famous $J = J_1 \sin \varphi$ relation-see box on page 24.) I think it was residual uneasiness on this score that caused the two Brians (Pippard

Brian D. Josephson in 1969

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The Josephson effect

Superconducting tunneling. Oxidise a strip of superconducting film (say lead) very lightly to a depth of 10-20 A; then evaporate a cross strip of lead film. Simply plot the current-voltage characteristic of the resulting "tunnel junction." Electrons can tunnel quantum mechanically directly from an energy level in one piece of lead to an equal energy in the other. At temperatures less than T_C, the superconducting transition temperature, "normal" current does not flow very well until we apply enough voltage to overcome the energy gap 2Δ, because there are no single-particle levels in the gap.

Josephson effect. But Josephson showed that superconducting pairs of electrons can also tunnel, almost equally well. The supercurrent is $J = J_1 \sin \phi$, where J_1 is comparable with the "normal" current at $V = 2\Delta$. ϕ is the difference between the phases of the electron-pair "wave functions" in the two superconductors on opposite sides of the insulating barrier of oxide. Later it was realized that the phases are coupled by an energy $E = -E_1 \cos \phi$, that the minimum energy is achieved by equal phases and zero current. But an external current source can drive the phases unequal. If the phases are time independent, a dc supercurrent flows with no voltage drop. (See below.)

Superconductivity. The phenomenology of superconductivity can be summarized in terms of the phase ϕ of the pair wave functions. The superconducting electrons (usually most of them) move with a velocity v_s, which is given (except for a factor 2 in the vector-potential term) by the standard quantum-mechanical equation

$$v_s = \frac{\hbar}{m}\left(\nabla\phi - \frac{2e}{c}A\right)$$

If the phase is uniform, v_s is proportional to the vector potential A, which gives the standard London equation describing the Meissner effect of flux exclusion. The quantization of flux is just the requirement that ϕ be the phase of a single-valued function, so it may change only by $2n\pi$ or going around a ring. We see from this equation that either a magnetic field A or a current v_s can lead to a gradient of ϕ; either may be used in a Josephson interferometer.

The time dependence of the phase is given by the "Josephson equation"

$$\hbar\frac{d\phi}{dt} = 2eV$$

which is just the Einstein equation relating frequency to the energy of a pair. This equation, together with the previous one, shows that a voltage can not be maintained across a superconductor without accelerating the supercurrent. This equation, together with the Josephson-current equation, allows us to measure e/h from the relationship between voltage and the frequency of the ac Josephson current that flows when we maintain a voltage across the junction.

Josephson penetration depth. The Josephson current can itself cause a magnetic field that modulates ϕ. The resulting coupling leads to a modified kind of Meissner effect with a long characteristic length λ_J. Junctions larger than λ_J behave like bulk superconductors in some ways.

and Josephson) to decide to send the paper to *Physics Letters*,[2] which was just then starting publications, rather than to *Physical Review Letters.*

Earlier in my course I had made some remarks about broken symmetry, and later we discussed how broken symmetry made this peculiar behavior of the current possible. Josephson has always given me much more credit for these remarks than my understanding at the time deserved. Apart from these ideas about broken symmetry and some very minor points acknowledged explicitly in that *Physics Letters* paper, I want to emphasize that the whole achievement, from the conception to the explicit calculation to the publication, was completely Josephson's.

I hope it was no coincidence that these developments occurred in the thoughtful and stimulating atmosphere characteristic of the Cavendish. But the specific achievement was Josephson's own; this young man of 22 conceived this entire thing and carried it through to a successful conclusion.

Two things about that original paper have always struck me as remarkable. The first one is that, from the original idea of a dc supercurrent, he should immediately make the all-important leap not only to the ac supercurrent but also to the mathematics of how to synchronize it with an external ac signal. Furthermore, he explained how to observe the effect in exactly the way that Sidney Shapiro did nearly two years later,[3] and so predicted what is now the standard method for measuring *e/h*. The second remarkable thing was the initial response of our excellent patent lawyer at Bell Telephone Laboratories when John Rowell and I consulted him; in his opinion Josephson's paper was so complete that no one else was ever going to be very successful in patenting any substantial aspect of the Josephson effect.

Let me then complete the history. At this point I have to start looking at things from my own point of view, which was that I was extremely enthusiastic about what Josephson had done and eager to work on it, I believe I was probably the most enthusiastic evangelist for the effect that he had. Therefore this narrative will now begin to sound like a description of what I did with the Josephson effect, But of course at the same time other lines of development were being followed, lines I had nothing to do with.

After a few more discussions at the Cavendish, which did not carry us much further than what had been published in the first paper, I returned home to Bell Labs. There I mentioned to Rowell my conviction that Josephson was right. Rowell admitted to me that he had, from time to time, seen suggestive things in his tunnel junctions, and a few months later he called me in to look at his experimental results on a new batch of tunnel junctions. He thought he might actually be seeing the Josephson effect. In thinking at that time about the results of Rowell's measurements the penny finally dropped for me, and the only two remaining essential components of the phenomenon became clear.

The first of these is that $J = J_1 \sin \varphi$ implied a coupling energy between the two superconductors of $E = E_1 \cos \varphi$. The value of E_1 is a very vital point; it must be larger than the noise energy in the circuit, which is why our experiments with low-resistance junctions worked and previous attempts by Josephson and others with higher resistance junctions, and thus smaller J_1 and E_1, had not been successful. The second new idea was the Josephson penetration depth.

Looking back, I assume that many workers must have observed the coupling-energy effect previously, but the point is that this effect is not easy to distinguish from a tunnel junction shorted across the layer separating the two metals. We were able to see the effect because three conditions were satisfied: First, we knew what to look for; second, we understood what we saw. Both of these were the result of our contact with Josephson. The third condition was that we were confident of Rowell's skills in making good, clean, reliable, tunnel junctions.

After we understood these theoretical ideas we changed the title of our paper[4] from "Possible . . ." to "Probable Observation of the Josephson Effect."

Publication

The story of the publication of these various ideas is complicated. I soon learned that the two ideas I have just mentioned had both been discovered and written out by Josephson several months earlier. The history of how they were published is a kind of "Alphonse-Gaston" story.

The first time they were written down was in August 1962. Josephson submitted, in support of an application for a research fellowship at Trinity College, Cambridge, a "fellowship thesis" that contained the first really full, account of the general nature and the physical meaning of the Josephson effect. This paper also contained the generalization to nontunneling situations, which I later called "weak superconductivity," One copy of this thesis remains, I believe, in the Trinity College library; one copy Josephson kept, and for some reason a photostat copy turned up in Chicago. Later on, after we did the experiments, I received a copy also. But the first three copies represented what Josephson felt to be adequate publication. Perhaps I am not being quite fair, because most of these ideas were included in Josephson's remarks at the LT8 conference in London, September 1962, in a rather famous debate with John Bardeen.

I had reproduced some of these results but, knowing after the fact about Josephson's thesis, I did not want to call too much attention to my own work of several months later. Therefore I published by own full version[5] in the notes of the Ravello Summer School of May 1963, which took almost two years to appear in print.

Neither of these two roughly equivalent papers is widely quoted, to say the least. That is a pity, because together they contain many things that had to be rediscovered later. I find in my file of letters from Josephson that we discussed the possibility of a joint paper, but this seems not to have come off.

Significance

This is enough reminiscence; what has turned out to be the significance of Josephson's discovery? I think two analogies may help to show how important it is. Imagine, for one, that we had developed a purely theoretical geophysical model of the earth that predicted the existence of a magnetic field, but imagine in addition that no one had yet invented the compass! I like that analogy because it shows up both aspects of the importance of a measuring instrument-and the Josephson effect is first and foremost a measuring instrument. The measuring instrument is important because, first, it verifies the theory, and second, it suggests a host of practical uses.

The second analogy for the significance of the Josephson effect is somewhat deeper. Suppose we understood the wave nature of light theoretically, and had even developed the laser, but no one had ever invented a way to get the light beam out without completely messing up the laser oscillations. That is, suppose no one had invented slits, half-silvered mirrors and all the other paraphernalia of interference experiments. We should then be in the same frustrating position that we were in with regard to superconductivity before Josephson. Then we had a theory and sources of coherent radiation, but no measuring instruments or gadgets to verify the theory and make use of the coherence.

In 1962 we had already postulated that superconductivity consisted of a coherence of the de Broglic waves representing pairs of electrons inside the superconductor. Prior to Josephson, the phase φ of these macroscopic waves was thought to be unmeasurable in principle, by the same kind of specious reasoning that has been used to prove such things as the nonexistence of ferroelectricity. In principle the phase varies with magnetic field and current in space according to the equations

velocity of superelectrons v_s

$$= \frac{\hbar}{m}\left(\nabla\varphi - \frac{2e}{c}\mathbf{A}\right)$$

and in time according to the Einstein-Josephson equation

$$\hbar\omega = \text{energy}$$

That is,

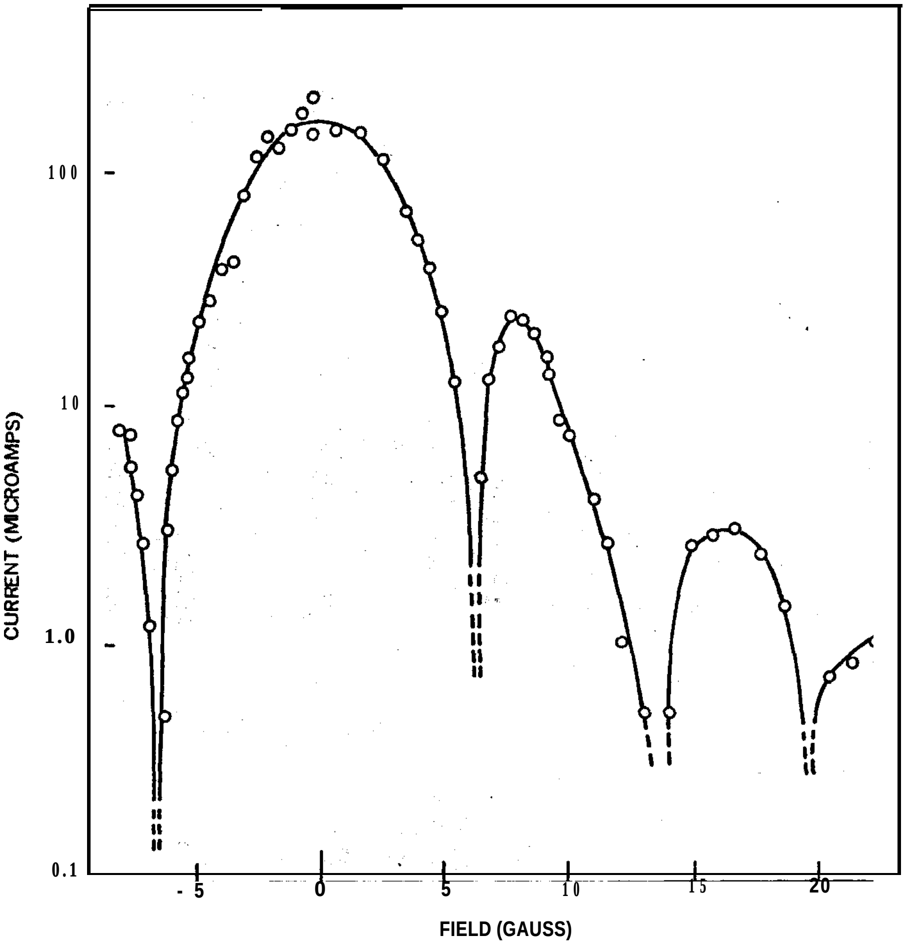
$$\hbar \frac{d\varphi}{dt} = 2\mu_e + 2eV$$

where μ_e is the chemical potential.

It was not yet entirely clear at the time that these two equations are equivalent to our theoretical understanding of superconductivity. The second equation predicts zero resistance in the absense of acceleration $(d\varphi/dt)$, and the first leads to the Meissner effect and to flux quantization.

The four equations in the box on page 24 tell us all we ever need to know about the Josephson effect and most of what we need to know about superconductivity. The first two equations give us a way of comparing the phases of two weakly coupled bits of superconductor, if they are so weakly coupled that they do not seriously perturb one another.

The straightforward way to verify the Josephson effect is simply by observing the superconducting tunnel current between two bits of superconductor. It is important that the junction really be a tunnel junction. Josephson's theory predicts a certain magnitude for the tunnel current. We began[4] by making this observation, which is simple theoretically but not very elegant experi-



Single-slit interference pattern shows dependence of Josephson current in a lead-lead-oxide-lead junction on magnetic field at 1.3 K. From reference 6. Figure 1

mentally. A more convincing verification[6] is the observation of the single-slit interference pattern caused by a small, steady change in the magnetic field near the sample. The change in magnetic field gives a linear variation of phase across the sample in the same way that changing the angle of observation across a slit gives a linear change in phase across the slit.

Figure 1 shows an observation of this pattern, made by Rowell in 1963 with the best junctions he was at that time able to produce.[6] The extremely deep minima attest to the high uniformity of his junctions. The original observations of this effect, made by Rowell in December 1962, were comparatively crude. He simply observed the changes in the tunneling current on a recorder while he slid a bar magnet along the surface of a table towards the sample, Again from my file of correspondence with Josephson I note that he also had suggested this observation before he had any way of knowing that we were in the process of carrying it out.

In principle the next thing to do is the two-slit experiment. This was conceived and carried out[7] in many fascinating versions by the group of Robert Jaklevic, James Mercereau, Arnold Silver and John Lambe at the Ford Laboratories. Figure 2 shows their two-slit pattern, obtained as a function of v_s, which is proportional to the current through one arm of a loop containing a pair of junctions. In addition they observed the pattern in three other ways-as a function of the magnetic field alone, as a function of the vector potential in the absence of a field and as a function of the velocity of the superelectrons imparted through rotation.

The final coup verifying the Josephson effect was carried out[3] by Sidney Shapiro, of the A. D. Little Co, actually before the two-slit experiments were done. Shapiro applied an external ac signal to the junction and observed the points of synchronization with the internal ac supercurrent. Figure 3 shows the results of a similar experiment carried out later[8] with a thin-film bridge by Ali Dayem and myself; this geometry greatly enhances the coupling to external rf fields.

I do not think one should underestimate the impact of the Josephson discovery on our understanding of superfluidity and superconductivity. One example of great importance is in the study of dissipative phenomena. The idea and the experimental verification of flux and vortex quantization, and the Josephson frequency condition, already existed in the literature. It was the direct tangibility given them by the experimental access that made us put them together in the two phenomena, seemingly diverse, of high-field superconducting magnets and dissipation in superfluid helium.[9] In each case the key to what is going on in the dissipative effects is the Josephson frequency condition and the idea of phase slippage by vortex motion.

Applications

We have now reached the third stage of the application of Josephson's discovery, after a zeroth stage consisting of his predictions, a first stage of verification and a second stage of generalization and conceptualization. This third stage is practical application, which of course means scientific application in other fields as well.

At present by far the most famous application is the measurement of h/e, as suggested by Josephson himself very early and as carried out[10] by Donald Langenberg, Barry Taylor and William Parker of the University of Pennsylvania. The story of this measurement is too well known to bear repetition; I should say only that, from the first, all of us in the field have felt that it was only a matter of time before the most accurate standard of voltage measurement became the comparison with frequency via Josephson's equation. This role is analogous to that of light interferometry in length measurements.

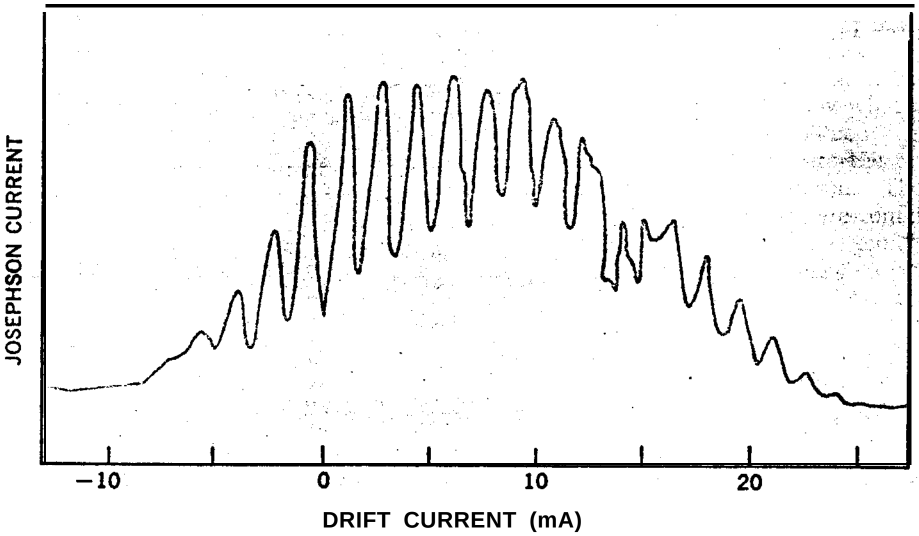
We can assume that h/m_e and h/m_{He}, two more constants that can also be measured by Josephson experiments, will also fall to sufficiently ingenious and careful experimentalists. The experiment for h/m_e, in particular, is very clean; one has only to count and to measure an area. Parker has already done this experiment to an accuracy of 10^{-4}. I see no reason why the major portion of our system of units should not be basically defined in the future by two kinds of interferometry-Josephson interferometry and light interferometry.

Perhaps even more important will be the role of the effect in ultrasensitive electromagnetic (and, with liquid helium, gravitational) measurements. The pioneering work of Jaklevic, Mercereau and their coworkers has been followed by the development, at the Mond Laboratory at Cambridge, of the SLUG picovoltmeter by John Clarke.[11] This instrument can measure voltages such as those that arise from the resistance of a 10-nanometer (100-angstrom) copper film normal to its area from one superconductor to another. I have no idea what further plans for ultrasensitive measurements are on the drawing board. But it is a bit frightening to realize that Clarke's voltmeter was a success because he deliberately reduced the sensitivity to make the instrument easier to handle!

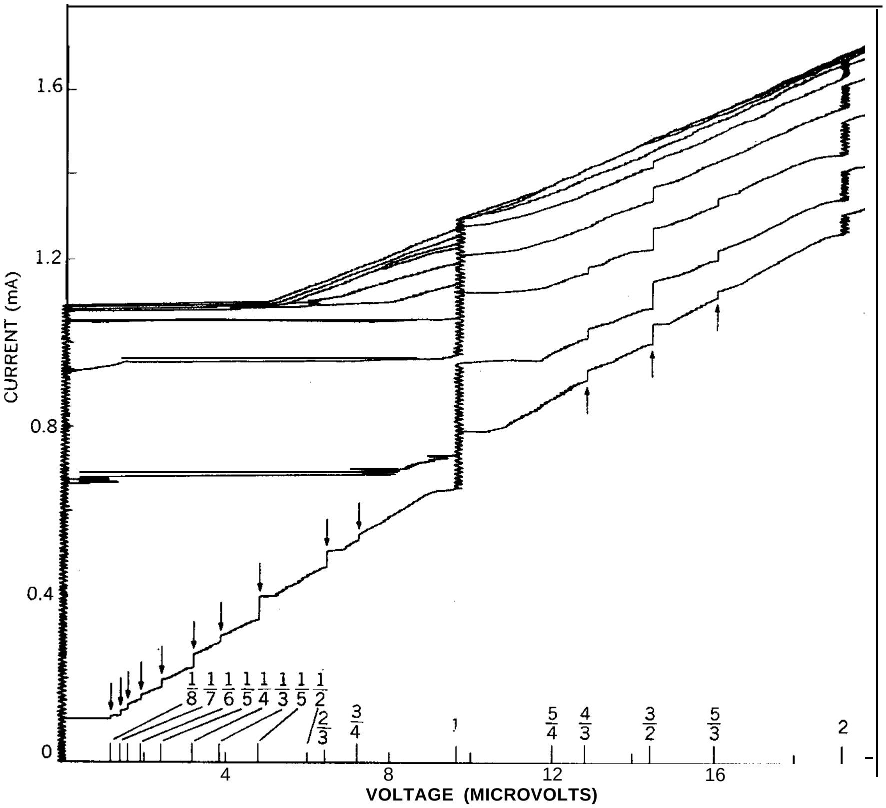
A third promising direction is in the detection and demodulation of high-frequency radiation, pioneered at Bell Labs by Dayem, Shapiro, Mike Grimes and Paul Richards.[12] So far the natural convenience of the ac Josephson effect as a direct frequency-to-voltage converter (the relation is directly linear) has not been fully exploited, but great promise exists.

The use of the Josephson effect as a high-frequency generator has been discussed widely, but I have a faint personal prejudice against such a use. It appears to me to be a crude application for this delicate effect. Of course I hope I shall be proved wrong and the ac generator will turn out to be highly valuable in the region between the microwave and the infrared frequencies.

Perhaps the wildest application yet is at the General Electric research labora-



Interference and diffraction effects in two thin tin films separated by an oxide layer, vacuum deposited on a quartz substrate in such a way as to give two junctions connected in parallel. This experimental trace of Josephson current versus drift current at 3.7 K shows the two-slit pattern. Maximum current is 1.5 mA. Zero offset arises from a static applied field. **Figure 2**



Effect of an external ac signal. These are current-voltage characteristics for a thin-film bridge of indium subjected to a 4.26-GHz external signal. The steps in the characteristic curves are induced at voltages $V = nh\nu/2me$. Fractions in color are values of *n*/*m*. The separate curves are for different power levels. From A. H. Davem. J. J. Wiegand, Phys. Rev. 155, 419 (1967). Figure 3

tories at Schenectady, where Ivar Giaever[13] has a light-sensitive Josephson junction that can be switched on with light.

An application I have been advocating for many years would involve using Josephson junctions for the control and movement of single quantized vortex lines as computer elements, rather like the recent "bubble" devices developed at Bell Labs. Rough calculations indicate great advantages in size and speed, but so far no real work has been done on such systems. The technology is challenging, to say the least.

With these last speculative comments I have tried to convey the impression that the Josephson effect is not a closed subject but still very much open-ended. The technology as well as the science of the future is likely to depend greatly on macroscopic quantum interference of matter waves, the discovery and exploitation of which we owe in large part to Brian Josephson.

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