Predicted in 1962 by a British graduate student, these two unusual manifestations of the superconducting state have now been observed directly. Their theoretical and technological significance is discussed by Donald N. Langenberg, Douglas J. Scalapino and Barry N. Taylor.

Four years ago Brian D. Josephson, a young graduate student in physics at the University of Cambridge, made a startling prediction. On the basis of a purely theoretical analysis of the phenomenon of superconductivity (the abrupt disappearance of electrical resistance in certain substances at temperatures near absolute zero) Josephson came to the conclusion that in principle a "supercurrent" consisting of correlated pairs of electrons could be made to flow across an insulating gap between two superconducting bodies, provided that the gap was small enough. He further suggested that this "tunneling" of electrons through an insulator could take two forms, which have come to be known as the Josephson effects. Both forms have been observed in recent experiments.

The nature of the Josephson effects can be understood in a general way by considering what happens when an electric current flows in a superconductor [see illustration on page 32]. If a direct current is made to flow in a bar consisting of a superconducting substance a voltmeter connected across the ends of the bar will indicate that the drop in voltage across the bar is zero; thus the bar has no resistance and is said to be in the superconducting state.

If the bar is now divided in two and the pieces are separated by a distance of, say, a centimeter, no current will flow in the opened circuit, and the voltmeter will indicate a voltage equal to the open-circuit voltage of the current source (for example a battery).

If the distance between the two pieces is reduced to about 10 angstrom units, however, one of two surprising things can happen: the first is that the voltmeter shows no voltage between the two pieces of superconductor but a direct current is observed to flow in the circuit even though the two pieces are still physically separated. In other words, the current can flow without resistance not only through the two pieces of superconductor but also across the gap between them. This phenomena is called the d.c. Josephson effect.

The second thing that can happen is that a direct current flow in the circuit but the voltmeter indicates a voltage. Simultaneously very high-frequency electromagnetic radiation emanates from the gap indicating the presence in the gap of a very high-frequency alternating current. This phenomena is called the a.c. Josephson effect. Like the d.c. effect, the a.c. effect is a direct consequence of the unique nature of the superconducting state.

The investigation of the two effects has already made important contributions to our understanding of superconductivity, and it now appears that they may also have useful applications in technology. Such applications include devices for generating extremely short-wavelength electromagnetic radiation for measuring very small magnetic fields and for providing highly precise voltage references. Perhaps more important, the Josephson effects may enable physicists to gain an even deeper understanding of superconductivity and to measure some of the fundamental constants of physics with an accuracy never before achieved. Before discussing in detail these somewhat exotic phenomena and their connection with superconductivity, we should like to review some of the salient features of the superconducting state.

The phenomenon of superconductivity was discovered in 1911 by Heike Kamerlingh Onnes of the Netherlands. He observed that in a sample of mercury all resistance to the flow of electric current vanished when the sample was cooled below a characteristic temperature (now called the superconducting transition temperature). Since 1911 the number of known superconductors has grown to several hundred and includes a number of metallic elements many metallic alloys and even a few semiconductors. The transition temperatures of all known superconductors lie below 20 degrees Kelvin (degrees centigrade above absolute zero), and in most cases the transition temperature rises below 5 degrees K., a temperature region that is accessible only by using liquid helium as a refrigerant or by resorting to more sophisticated techniques. The experimental study of superconductivity therefore lies in the realm of low-temperature physics.

For several decades after Onnes' discovery it was believed that a metal in
the superconducting state could be characterized simply as a metal with zero electrical resistance or infinite electrical conductivity. Then in 1933 the German investigators W. Meissner and R. Ochsenfeld discovered that there is more to it than that. They found that an externally applied magnetic field is excluded from a super-conductor either when it is cooled below its transition temperature in the presence of the field or when the field is applied after the substance has become superconducting. A substance with infinite conductivity would exhibit the latter behavior but not the former; it would "tend to freeze in" any field present when it became superconducting, not expel it. This effect, now called the Meissner effect, is therefore not a consequence of infinite conductivity but a distinct and perhaps more fundamental property of the superconducting state.

The existence of the Meissner effect and certain other properties of superconductors led the theoretical physicist Fritz London to a highly significant insight into the nature of superconductivity. He suggested in 1935 that the superconducting state is a manifestation of quantum mechanics operating on a macroscopic scale—a state, with long-range order; in which the motions of a significant fraction of the electrons throughout the entire bulk of the superconductor are correlated. Thus a piece of metal in the superconducting state is in some respects like a single giant molecule. This idea led to a qualitative understanding of many of the unique properties of superconductors. It suggested, for example, an explanation for the characteristic infinite conductivity. A normal metal exhibits resistance to the flow of electric current because any concerted motion of the electrons in one direction is dissipated rapidly by the scattering of individual electrons from the vibrating atoms of the metal or from impurities of imperfections in its structure. If the electrons are in a state in which the motion of each electron is correlated with the motions of all the other electrons, however, and if this correlation extends throughout the metal, the scattering of one electron will necessarily involve all the others. This "united we stand, divided we fall" property makes the scattering of electrons impossible or at least highly improbable, and a supercurrent flow, once started, is immune to the scattering that retards normal currents.

Although London's idea provided physicists with a new and fruitful viewpoint on superconductivity, the microscopic origin and nature of the superconducting state was not really understood until 1957, when John Bardeen, L. N. Cooper and J. R. Schrieffer, then at the University of Illinois, published a now famous theoretical paper on superconductivity. According to their theory, superconductivity occurs because of the existence of an attractive force between the electrons in a metal. Although electrons, each having a negative charge, repel each other in free space, this need not be the case in a metal. There a negatively charged elec-
JOSEPHSON EFFECTS can be understood in a general way by considering what happens when an electric current flows in a superconductor. The absence of resistance in a superconductor is demonstrated by the fact that no voltage drop appears across a superconducting bar when a direct current is made to flow through it \( (a) \). If the bar is divided into two and the pieces are separated by a distance of say, a centimeter \( (b) \), no current will flow in the open circuit, but the voltmeter will indicate a voltage equal to the open-circuit voltage of the current source (in this case a battery). If the distance between the two pieces is reduced to about 10 angstroms, however, one of two surprising things can happen. The first is that the voltmeter shows no voltage between the two pieces of superconductor but a direct current is observed to flow in the circuit even though the two pieces are still physically separated \( (c) \). This phenomenon is called the d.c. Josephson effect. The second thing that can happen is that a direct current in the circuit but the voltmeter indicates a voltage \( (d) \). Simultaneously very high-frequency radiation emanates from the gap, indicating the presence in the gap of a very high-frequency alternating current. This phenomenon is called the a.c. Josephson effect.

Electrons moving through a lattice of metal ions, attract the positively charged ions. This distorts the lattice, creating a wake of excess charge to which another electron can be attracted. Thus in a metal there can be, in addition to the usual repulsive force between electrons, an indirect attractive force that arises from the lattice of metal ions. In order for a metal to be a superconductor, this lattice-mediated attractive force must exceed the repulsive force—the net interaction of electrons must be attractive.

The involvement of the lattice in the attractive interaction explains the seemingly peculiar fact that superconductivity has never been observed in the metals that are usually considered to be the best conductors; such as copper and silver, whereas it is a common phenomenon among the poorer conductors, such as lead and tin. The high conductivity of copper and silver is a consequence of the comparatively weak interaction of electrons with the lattice in these metals. This reduces the scattering of single electrons that impairs conductivity in the normal or nonsuperconducting state, but it also reduces the attractive interactions of electrons that leads to superconductivity.

The attractive force tends to couple together in “bound pairs” electrons that have equal and opposite momentum and spin. This binding is extremely weak, however, as revealed by the fact that it is disrupted, and superconductivity is destroyed, by thermal disorder at temperatures just a few degrees above absolute zero. Because the attraction is weak the two paired electrons, on the average, separated by a distance that is thousands of times greater than the distance between the lattice ions. Since there are usually several electrons for each ion, the electrons of each bound pair range over a volume that simultaneously contains millions of other electron pairs. This spatial overlapping of the pairs has important consequences that arise primarily from the principle of quantum mechanics called the exclusion principle, which states that two electrons with the same spin cannot occupy the same spatial position. If the requirements of the exclusion principle are to be met, the motions of the pairs must be correlated. The Landau-Cooper-Schrieffer theory showed that the correlation is accomplished if the centers of mass of all the pairs move with the same momentum. This is one of the center-of-mass momentum of the bound electron pairs throughout the superconductor is the long-range one envisioned by London. All the electron pairs are locked together by the requirement that they have a common center-of-mass momentum. Disturbing one pair disturbs all the pairs, because of the cooperative nature of this momentum-ordering.

In the quantum-mechanical description of this ordering the wave aspects of electrons must be taken into account. An electron pair with a center-of-mass momentum \( \mathbf{p} \) can be described by a wave with wavelength \( h/\mathbf{p} \), where \( h \) is Planck’s constant. In terms of the quantum-mechanical wave picture, equality...
The phase of a periodic motion is a measure of the fractional number of cycles (multiplied by 2π) through which the system has advanced from some arbitrary but fixed reference configuration. An example that may clarify the meaning of phase is a rotating wheel with one colored spoke [see lower illustration on this page]. Taking as a reference the position in which the colored spoke is vertically down (position 1), the phase is indicated for several different configurations. For example, in position 2 the wheel has turned through half a cycle, and we say the phase has advanced by π. It is clear, comparing position 1 and position 4, that the physical configuration of the wheel is the same for a phase equal to zero and a phase equal to 2π. We say that the phase of position 1 and position 4 are the same with respect to the “modulus” 2π. The motion of the wheel depends on the way the phase develops in time. For example, if the phase of the wheel varies linearly with time, the wheel rotates at constant speed. The time interval during which the wheel completes a cycle and the phase increases by 2π is called the period of the motion.

In general, a system can be periodic in space as well as in time. An example is the displacement of the surface of a pond when a wave is created by dropping a pebble. The phase of such a wave depends on both the spatial distance and the time lapse with respect to some reference point in space and time. In the top illustration on the opposite page the space and time development of a simple sinusoidal wave is shown. The wavelength of the disturbance is the distance over which one spatial oscillation occurs and the phase of the displacement changes by 2π. The period is the time interval over which one temporal oscillation occurs and the phase of the displacement changes by 2π. The phase at several points on the wave is given with respect to the point of origin. The broken line shows the space-time development of a particular point of constant phase, the one corresponding to zero phase. The rate at which this point of constant phase moves in space is called the phase velocity of the wave.

Now, as we have mentioned, according to quantum mechanics the wave associated with an electron pair has a spatial oscillation whose wavelength is determined by the center-of-mass momentum of the pair. The wave also has a time oscillation whose period is determined by the energy of the electron pair, so that the phase of the pair depends on the pair’s energy as well as on its center-of-mass momentum. As we have seen, in a bulk superconductor the attractive interaction of electrons, the large number of bound electron pairs and the exclusion principle conspire to make the pair phases the same. These two facts lead to a simple explanation of the zero resistance of 'the superconducting state: If a voltage difference V existed between the two ends of the current-carrying superconducting bar shown in the illustration on the opposite page, the energy of an electron pair in one end would be greater by 2eV than the energy of an electron pair in the other end (e is the charge of an electron). Then, as time passed, a phase difference would develop between the electron pairs in the two ends of the bar. Rather than go to the higher energy state that this breakdown of the pair phase-locking would produce, the superconductor carries the current with-
A traveling wave, that is, one that varies periodically in both space and time, is shown here for a simple sinusoidal disturbance analogous to the ripples produced on the surface of a pond by dropping in a pebble. The wavelength is the distance over which one spatial oscillation occurs. The period is the time interval over which one temporal oscillation occurs. The phase at several points on the wave is given with respect to point of origin \(0\), Broken line shows space-time development of a particular point of constant phase, the one corresponding to zero phase. The rate at which this point moves in space is called the phase velocity of the wave. According to quantum mechanics the wave associated with an electron pair in a superconductor has a spatial oscillation, whose wavelength is determined by the pair’s center-of-mass momentum, and a time oscillation, whose period is determined by the pair’s energy.

PROCEDURE for fabricating a Josephson junction begins with the deposition of four electrodes, in the form of thin metal films, on a slide (1). This is done by heating the metal in a vacuum chamber until some of it evaporates; the resulting metallic vapor is passed through a mask before being deposited on the slide. Next a thin film of a superconducting substance (for example tin) is deposited on the slide in the form of a strip that makes contact with two of the previously deposited electrodes (2). The strip is typically one millimeter wide and about 2,000 angstroms thick. The third step is the formation of a very thin layer (about 10 angstroms thick) of insulating oxide on the surface of the bottom strip (3). This is accomplished by admitting a carefully controlled amount of air or pure oxygen to the vacuum chamber. The junction is completed by depositing a second strip of superconductor on top of the oxide layer, usually at right angles to the bottom strip (4). This strip makes contact with the two remaining electrodes. Wires for supplying a current to the junction and for measuring the voltage drop across the junction are then soldered to the electrodes.
out allowing a voltage difference to appear.

What Josephson did in 1962 was to 

perceive that it should be possible 
to modify the phase-locking and hence 
study in detail this aspect of the superconducting long-range order. He consid-
ered the situation shown in the illustra-
tion on page 32 and argued as follows: The pair phase must be the same 
throughout a single piece of supercon-
ductor, since pairs can move freely 
through it. If the superconductor is 
divided into two pieces and the pieces 
are well separated so that pairs cannot 
be exchanged between them, there need 
be no particular relation between the 
pair phases of the two pieces. If the 
two superconductors can be brought 
close enough together, however, an in-
termediate situation will result in which 
there can be some exchange of electron 
pairs by means of the quantum-mechani-
cal process called tunneling. (Because 
of their wavelike nature, electrons can 
tunnel, or penetrate, through barriers 
they could not penetrate if they were 
simply particles.) In this case the overall 
system can assume a state of minimum 
energy in which there is a unique differ-
ence between the pair phases in the 
two superconductors. It should then be 
possible to vary this phase difference, or 
relative phase, by controlling the rate 
of pair transfer between the two pieces 
of superconductor.

The intermediate situation can in 
principle be achieved simply by separ-
ating the two pieces by a distance on 
the order of 10 angstroms. Unfortu-
nately no one actually knows how to 
construct such an arrangement, but a 
completely equivalent one can be rea-
nized in practice using a procedure de-
veloped by Ivar Ciaever and John C. 
Fisher of the General Electric Research 
Laboratory [see bottom illustration on 
opposite page]. The essential feature of 
the technique is that the two supercon-
ductors are separated by a thin layer of 
insulating oxide, which is allowed 
to form on one of them before the other 
is deposited on top. The result is a 
metal-insulator-metal sandwich with 
superconducting bread and insulating 
salami. Such a structure is called a 
tunnel junction [see illustration on page 
30]. The tunneling of pairs between 
the two superconductors of such a junc-
tion leads to a coupling of the pair 
phases on the two sides, which can be 
modified by electric and magnetic 
fields as Josephson envisioned.

Josephson predicted that if somehow 
a phase difference is produced between 

\[
\begin{array}{cccccc}
\text{PHASE OF PAIRS IN A} & \text{PHASE OF PAIRS IN B} & \text{CHANGE IN PHASE THROUGH OXIDE LAYER} & \text{PHASE OF PAIR AFTER GOING FROM A TO B} & \text{PHASE OF PAIR AFTER GOING FROM B TO A} & \text{JOSEPHSON CURRENT (MAXIMUM EQUALS } j_1) \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & \pi/4 & \pi/4 & \pi/4 & \pi/2 & \frac{j_1}{\sqrt{2}} \\
0 & \pi/2 & \pi/2 & \pi/2 & \pi & j_1 \\
0 & 3\pi/4 & 3\pi/4 & 3\pi/4 & 3\pi/2 & \frac{j_1}{\sqrt{2}} \\
0 & \pi & \pi & \pi & 2\pi & 0 \\
\end{array}
\]

PERIODIC RELATION between the junction current density and the pair phase differ-
ence can be understood by remembering that the phase of a pair depends on its motion. 
The schematic diagram at top shows two superconductors, labeled A and B, separated by 
an insulating oxide layer. The table at bottom shows how the transfer of electron pairs 
from A to B and from B to A is related to the difference in the pair phases in the two super-
conductors; it also indicates the net current for this relative pair phase. The pair phase in 
superconductor A is taken to be zero. If the pair phase in superconductor B is also zero 
(first line in table), the transfer of pairs in either direction is equally likely and the net 
junction current will be zero. In the second line of the table the situation for a pair phase 
of \(\pi/4\) in superconductor B is shown. The change in phase of a pair that traverses the oxide 
layer is \(\pi/4\). The phase of a pair going from A to B thus changes from zero to \(\pi/4\); when 

it reaches side B, its phase exactly matches, the phase on side B, it fits in nicely with the 
other pairs on side B, and such a transfer is relatively probable. The phase of a pair going 
from B to A, however, changes from \(\pi/4\) to \(\pi/4\), which does not match well with the 
zero pair phase of the other pairs on side A. The transfer of a pair from B to A is therefore not 
as likely to occur as the transfer of a pair from A to B. On the average there will be a net 
flow of pairs from B to A and hence a current. The phase mismatch for pairs going from 
B to A in the third line of the table is even worse, and therefore the number of pairs going 
from B to A is less. Consequently the net current from A to B is increased. 
The relative pair phase continues to increase in lines four and five, the mismatch is reduced and net cur-
rent from A to B decreases again. Table describes first half-cycle of curve at top of page.
The first indisputable experimental confirmation of the d.c. Josephson effect was reported in 1963 by John Rowell of the Bell Telephone Laboratories. He observed the predicted resistanceless current flow in a junction and studied its dependence on an externally applied magnetic field. Observation of the magnetic-field dependence was essential, because such a resistanceless current could also be due to the presence of small "bridges" of superconductor across the junction. Indeed, it appears in retrospect that many workers had observed the d.c. Josephson effect but had ascribed the resistanceless currents they observed to such bridges.
a unique periodic variation in quite small magnetic fields. This variation arises in the following way.

In quantum mechanics, the phase of the wave associated with a particle (or a bound electron pair in a superconductor) depends on the magnetic field (more precisely, on something called the magnetic vector potential). It turns out that if there is a magnetic field in a tunnel junction, the difference between the pair phases in the two superconductors has a spatial variation. If the field happens to be uniform and constant throughout the junction oxide layer, the phase varies in the plane of the junction in a direction at right angles to the direction of the field and at a rate proportional to the magnitude of the field. Because of the periodic dependence of the current density on the phase, the direct current in the junction oscillates in space and may reverse its direction at several points in the junction if the magnetic field is large enough. The maximum net resistanceless direct current that can be carried by the junction therefore varies periodically as the magnetic field is increased [see illustration on this page]. Rowell's observation of precisely this behavior clinched the identification of the observed resistanceless current as the d.c. Josephson effect.

So far we have considered only situations where the pair phase difference between the two superconductors of the junction does not vary in time. We have seen, however, that if there is a voltage difference and hence a potential-energy difference between the two superconductors, the phase difference will vary in time. The time-independent phase difference that exists when a direct current flows in the junction is in fact initially produced by a momentary voltage difference across the junction that occurs when an external current source is connected to it. The voltage drop causes the phase to shift in time. When the phase difference attains the value that corresponds to the current determined by the current source, the voltage drop vanishes, and the relative pair phase thereafter remains constant in time. This happens in about a ten-billionth of a second. If the current source forces the current to exceed the maximum d.c. Josephson current, however, a voltage appears across the junction, and the relative phase increases steadily in time. Because of the sinusoidal dependence of the Josephson current on the phase, the current oscillates back and forth between the two superconductors at a frequency proportional to the voltage across the junction. This is the a.c. Josephson effect.

Experimental confirmation of the a.c. Josephson effect has proved to be considerably more difficult than confirmation of the d.c. effect. The relation between the time dependence of the phase and the voltage across the junction is such that if the voltage has a constant value $V_0$, the frequency $v$ of the oscillating supercurrent is $2eV_0/\hbar$ times the voltage, where $e$ is the charge of an electron and $\hbar$ is Planck's constant (thus $v = 2eV_0/\hbar$). The ratio $2eV_0/\hbar$ is numerically equal to 483.6 megacycles per microvolt, and since typical junction voltages range from a few microvolts to several millivolts the frequency of the oscillating supercurrent can be as high as several hundred billion cycles per second. The obvious straightforward way to observe such high-frequency currents is to detect the electromagnetic waves radiated by the current. (In general any oscillating current will radiate electromagnetic waves.) At the frequencies involved the radiation is in the microwave and far-infrared regions of the electromagnetic spectrum. The amount of energy the a.c. Josephson currents radiate, however, is very small and thus rather difficult to detect. Consequently direct experimental confirmation of the a.c. Josephson effect came only after several indirect experiments had left little doubt that the effect really existed.

The first of these indirect confirmations was achieved in 1963 by S. Shapiro, then working for Arthur D. Little, Inc. Shapiro varied the voltage across the junction and measured the current through the junction while it was exposed to microwave radiation supplied by a conventional microwave oscillator. He found abrupt increases in the junction current at certain voltages. When these voltages were substituted into the Josephson frequency-voltage equation, $v = 2eV_0/\hbar$, the frequencies turned out to be whole-number multiples of the frequency of the applied microwave radiation.

This effect can be explained as follows: In addition to a d.c. voltage across the junction, there is also a small voltage induced by the applied microwave radiation that oscillates at the frequency of this radiation. Since the frequency of the Josephson supercurrent depends on the junction voltage, the supercurrent frequency has a small periodic variation in time; in other words, the supercurrent is -frequency-modulated. Because of this it contains components that have many frequencies. These frequencies are the algebraic sums of the frequency of the applied microwave radiation plus (or minus) the frequency

![Diagram of Josephson effect](image)
of the Josephson supercurrent plus (or minus) all the harmonic frequencies associated with these two fundamental frequencies. At d.c. voltages for which the Josephson frequency is equal to the microwave frequency or some whole-number multiple of it, among all the possible net frequencies there is one that is equal to zero. This means that there is a zero frequency or direct current at those values of d.c. junction voltage for which this special relation between Josephson frequency and microwave frequency occurs. All of this depends, of course, on the existence of the oscillating Josephson supercurrent in the first place, so that Shapiro’s observation represents an indirect confirmation of its existence.

Another indirect confirmation was provided by two of us (Scalapino and Taylor) and R. E. Eck at the University of Pennsylvania. It was observed that “steps,” or abrupt increases, in junction current were observed in the curves that related the current to the voltage of Josephson junctions, even in the absence of externally applied microwave radiation. This observation was an indirect confirmation of the existence of the a.c. Josephson effect. Each step corresponds to a “resonant mode” of the oscillating electromagnetic field that is present between the two superconducting strips in the junction.

Now, a Josephson junction is essentially an electromagnetic organ pipe. Electromagnetic waves can propagate between the two superconductors, and consequently a junction will have a set of resonant electromagnetic modes. A relatively intense electromagnetic field can be excited in the junction if the frequency and wavelength of the exciting source are adjusted so that they match the frequency and wavelength of one of these resonant modes. The origin of the steps observed by Eck, Scalapino and Taylor is now clear. The Josephson supercurrent can be made to vary periodically in space with a wavelength determined by an applied magnetic field, and periodically in time with a frequency determined by the voltage across the junction. When the frequency and wavelength of the supercurrent are thus matched to the frequency and wavelength of one of the junction modes, a large electromagnetic field will be generated in the junction. This field can then react on the Josephson current in the same manner as Shapiro’s applied microwave radiation to produce the observed steps in the current-voltage curve.

This discovery was important for two reasons. It provided additional indirect evidence for the existence of the a.c. Josephson effect, and it also provided a key to understanding how the a.c. supercurrent could be made to generate enough electromagnetic radiation in the junction to make possible direct external detection of the radiation. Armed with this knowledge, we embarked on an effort to achieve direct detection of radiation emitted by Josephson junctions. We have recently succeeded in doing so. The results of these experiments confirm in a very direct fashion the existence of the a.c. Josephson effect in superconductors and, perhaps more important, provide us with a powerful new tool for studying the effect.

In our experiments we chose to work at a frequency of about 10 billion cycles per second, because it is a commonly used microwave frequency and equipment and techniques for it are readily available and well known. The voltage corresponding to this frequency is about 20 microvolts. We therefore prepared junctions with the proper lengths so that the first or second resonant mode (or step in the current-voltage curve) occurred at 20 microvolts. These junctions were mounted inside a wave guide—a rectangular metal tube in which electromagnetic radiation can propagate. Wires were connected to the junction so that a d.c. voltage could be applied and the d.c. junction current could be measured. The wave guide and junction were inserted in a Dewar vessel (a vacuum-insulated container similar to a Thermos bottle) that could be filled with liquid helium for cooling the junction to a temperature one or two degrees above absolute zero. Outside the Dewar vessel there was a pair of coils for producing the necessary magnetic fields. The entire arrangement was surrounded by a magnetic shield to eliminate the earth’s magnetic field inside the Dewar vessel. Radiation emitted by the junction traveled inside the wave guide out of the Dewar vessel and into an electronic system that was designed to detect very small amounts of power. In one version this system could detect
of power in visible light received by a human eye from a 100-watt light bulb 300 miles away. Such high sensitivity was necessary because, although we knew how to make the Josephson supercurrent generate radiation inside the junction, we had not completely solved the problem of getting the radiation out of the junction and into the wave guide. Radiation propagating in the junction is almost entirely reflected back into the junction when it reaches the ends, and very little (only about one part in 100,000) -is radiated out into the waveguide.

This problem of optimizing the transfer of power from a source (the junction) to a load (the wave guide and the detection system) is an impedance-matching problem analogous to the problem of efficiently transferring power from a high-impedance high-fidelity amplifier to a low-impedance loudspeaker or from a low-impedance man to a high-impedance boulder. The solutions in these examples are impedance-matching devices: an electrical transformer in the first case and a lever or a block and tackle in the second. The solution for the Josephson junction is not so obvious, and we elected to sidestep this difficulty for the moment simply by using a detection system with a sensitivity adequate for detecting the power that was radiated. We estimated we might get perhaps a trillionth (10^{-12}) of a watt; the available sensitivity of 10^{-16} watt provided some insurance.

Once radiation was detected we were able to improve the power transfer somewhat and succeeded in observing up to 10^{-11} watt. A typical signal curve appears in the illustration at the right. As predicted by Josephson, the radiation was found to be coherent (all in phase) and at least as monochromatic as the radiation emitted by a conventional vacuum-tube klystron oscillator. The ratio of the frequency of the radiation to the d.c. junction voltage was found to be equal to the predicted value of 2e/h to an accuracy of better than 1 percent. Experiments that turn out exactly as expected are rare, however, and this one was no exception. Along with these comforting agreements between theory and experiment there appeared some surprises and some new puzzles which we are currently studying. Other workers are also active in the field. A group at the Ukrainian Academy of Sciences was the first to report a direct observation of radiation from a Josephson junction; they reported an observation of 10^{-13} watt of radiated further study of the Josephson radiation.

The direct detection of the a.c. Josephson radiation has opened up the possibility of several rather diverse applications. It provides a sensitive and direct tool for further study of the Josephson effects and superconductivity. For example, simultaneous measurements of the d.c. junction voltage and the frequency of the emitted radiation can yield a highly accurate check on the validity of the Josephson frequency-voltage relation. This is of considerable importance because the frequency-voltage relation is directly connected with some of the most fundamental features of the present theory of superconductivity. If the relation holds up under such careful scrutiny, the fundamental physical constant ratio e/h that appears in it can be determined with an accuracy several times greater than has heretofore been achieved. Here is a unique opportunity to use a macroscopic quantum phenomenon to determine one of the fundamental constants of nature. Experiments along these lines are now in progress in our laboratory.

There are also possible, applications in technology. The region of the electromagnetic spectrum between microwaves, with wavelengths measured in centimeters, and infrared waves, with wavelengths measured in micrometers, is still relatively unexplored. It has been hard for physicists to perform experiments using radiation in this part of the spectrum because the generation and detection of such radiation has been difficult and expensive. The Josephson junction has promise as a simple and inexpensive source of small amounts of coherent and monochromatic radiation with wavelengths ranging from several millimeters down to a fraction of a millimeter. It would be particularly useful in low-temperature experiments where liquid-helium cooling is already an essential part of the experiment. It will be necessary to solve the power transfer problem in order to obtain the desired powers, but there appear to be no obstacles in principle to doing this.

It has been only four years since Josephson discerned in the theory of superconductivity the effects that now bear his name. During those years the effects have received abundant experimental confirmation and have provided striking direct evidence of the wondrous workings of quantum mechanics on a macroscopic scale in superconductors. Our newfound ability to control the phase of superconducting pairs promises new advances in our understanding of superconductivity as well as benefits in other areas of physics and technology.

OUTPUT SIGNAL produced by the detection system associated with the authors' experiment appears on the face of an oscilloscope tube. The signal was produced by an input signal of a hundred-billionth of a watt of microwave radiation from a Josephson junction.