the Discovery of ELECTRON TUNNELING into SUPERCONDUCTORS

By Roland W. Schmitt

IN August 1960, Ivar Giaever published a discovery about electron tunneling into superconductors[1]; the discovery was elegant and had the esthetic simplicity that makes a scientist wonder why it had not been made before. It is too early to assess the importance of the discovery; it may be recorded as only a small but neat strand of science, or the train of work it has set off may produce a web of new knowledge about solids. Regardless of the final assessment that science makes of it, the discovery was surrounded by novel circumstances that dramatize the unexpected course of discovery.

Other physicists had come close to making the discovery or seemed on the verge of doing so: some had been doing similar experiments, but missed the discovery; some were looking for the wrong effect because of mistaken ideas; some were experimenting in the same field and, though not looking for a particular effect, could have stumbled on it. The experiment could have been done with equipment and techniques that were common a decade ago; it was not blocked by inadequate techniques and did not have to wait for the development of new research tools. Only a simple vacuum system for evaporating thin metallic films, a voltmeter, ammeter, and liquid helium were needed. The discovery was technically an easy one. Why, then, did the experiment remain undone during the previous decade while many physicists were working on superconductivity, including thin films? In spite of being simple, of being unblocked by technical complexities, of being in the arena of attention of many physicists, the discovery remained unsought and undetected until it was looked for and found by a young mechanical engineer just changing to a career in physics.

This story is the story of the discovery and the discoverer. I have only two reasons—other than the appeal of an entertaining story about research—for writing about the details of this microcosm in the history of science. Occupying an administrative post close to the people who played roles in the discovery, I had an intimate, but detached, view of the events that occurred. Also, in this story it is reasonably clear what was discovered and when it was discovered; what was new did not emerge slowly through the hazy fringes of discovery nor was it clouded by almost indistinguishable parallel discoveries. Goudsmit's fear that "when we try to look at a recent event with a microscope, the resolving power may often be insufficient"[2] does not hover too ominously in the background of this story. Except for these particular reasons, I make no claim that this story ought to be told any more than the stories of hundreds of other discoveries that go unreported.

THE history of superconductivity is a checkered one; it is characterized by long lapses between the major experimental discoveries and by an extraordinary hiatus between the original discovery and the first acceptable, fundamental theory of the phenomenon. Kammerlingh Onnes, in 1911 at Leiden, discovered superconductivity and found the characteristic property of zero resistance; he also learned that a high magnetic field would destroy superconductivity so that the state existed only at very low temperatures and in low magnetic fields. Another bulk property of superconductors remained hidden until 1933, when Meissner in Germany found it: in low magnetic fields, superconductors are perfect diamagnetics and expel all magnetic flux from their interior. The fundamental theory of the phenomenon still could not be developed in spite of intense efforts, but in 1950 the discovery of the isotope effect—a variation in the superconducting transition temperature with isotopic mass—confirmed an emerging suspicion of several theoreticians: that the interaction of electrons with lattice vibrations played the key role in producing superconductivity. Nevertheless, not until 1957, forty-six years after the original discovery, did Professor John Bardeen and two of his associates, Leon Cooper and J. Robert Schrieffer, develop a satisfactory theory of superconductivity.

One feature of this theoretical development is especially interesting for the story of electron tunneling into superconductors. The BCS theory, as it has come to be known, showed that a small but nonzero energy difference separated the first excited state of a superconductor from the ground state. Translated into the usual one-electron picture that physicists use when thinking about metals, this feature becomes a forbidden energy gap centered at the Fermi energy; in a superconductor, no electrons can have energies in this forbidden range.

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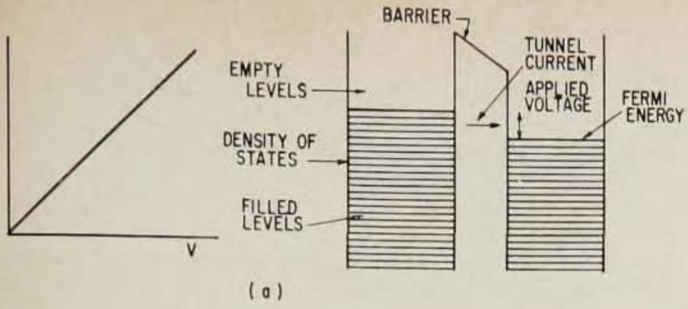
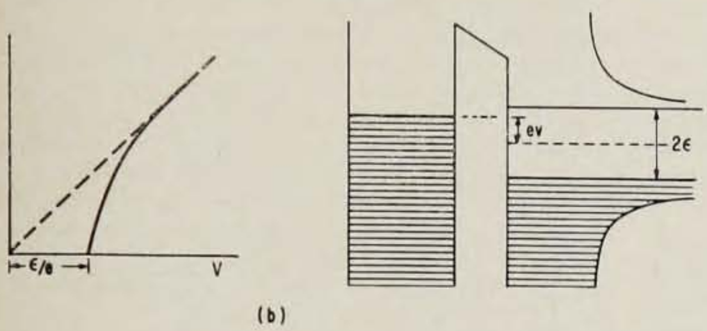


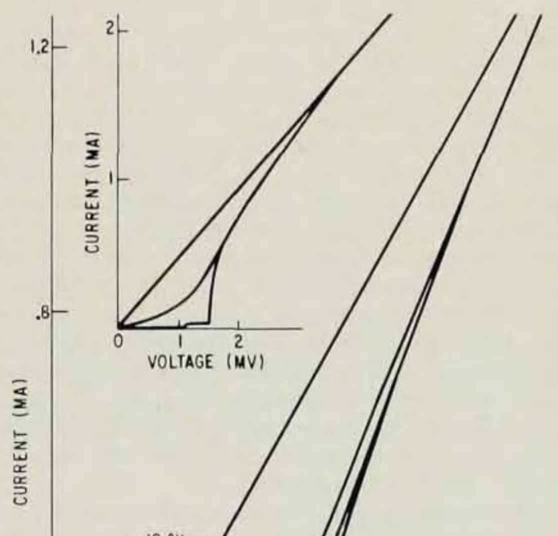
(a) The tunneling current between two normal metal films varies linearly with voltage at low voltages. As the voltage is increased, more and more filled levels of the metal film with negative bias are exposed (through the thin insulating barrier) to empty levels in the opposed metal film. This permits more and more electrons to tunnel through the barrier into empty states.



(b) The discovery. The forbidden energy gap at the Fermi level in superconductors prevents electrons from tunneling through the barrier into the superconductor until the biasing voltage exceeds half the gap width. The shape of the current-voltage curves measures the gap width and the density of states near the gap. The curve in this figure corresponds to $T = 0$.

Speculations about this energy gap reach back twenty years into the history of superconductivity, and experiments to detect it engaged physicists both before and after the BCS theory. The most convincing evidence for the gap came from studies of the way infrared radiation passed through or was absorbed by very thin films of superconductors.[3] These studies, carried out by Professor M. Tinkham and his students at Berkeley, demanded the most skillful experimental techniques; they needed talented experimentalists for their success.

The presence of the forbidden gap in superconductors means that if one tries to inject electrons with the forbidden energies into a superconductor, they will be rejected by it. Giaever showed this to be true with his experiment; it gave the most simple, direct evidence for the existence of the energy gap in superconductors and also gave information about the behavior of electrons with energies near the gap. The experiment is to inject electrons into a superconductor by letting them tunnel through a very thin, insulating barrier. Such a barrier allows one to vary the potential difference between the metal from which electrons are drawn and the metal into which they are injected and, therefore, makes it possible to vary the injection energy. Furthermore, the barrier prevents the free flow of electrons from the metal into the superconductor, as would occur with direct contact, but still allows single electrons to move through it one at a time. The original experiment used a thin, evaporated, aluminum film, coated with its own oxide and topped by another thin, evaporated film of lead. At the boiling point of helium, the lead, but not the aluminum, is superconducting. At very low voltages, almost no current flows through the junction because the energy of the injected electrons is in the forbidden energy range of electrons in the superconductor, but the current grows rapidly as the voltage



Experimental results showing tunneling current between aluminum and lead at various temperatures. At 10°K neither metal is superconductive, between 4.2°K and 1.3°K only lead is superconductive, and below 1.3°K both are superconductive.

reaches a value equal to half the width of the forbidden gap, for then the injection energies are equal to the allowed energy values in the superconductor. The current-voltage curve reveals directly the existence of the energy gap in superconductors and permits a simple measure of the size of this gap. With this elementary experiment, Giaever not only opened a new realm of experimental work on superconductors, but also created the hope of further discoveries about tunneling into metals, semimetals, and semiconductors.

The story behind the discovery begins in 1957. John C. Fisher became interested in the electronic properties of thin films; he talked about experimental possibilities with several people in our research group, but, because his main interest was different, there was no further activity until the latter part of 1958 when Giaever joined the section.

GIAEVER was born and educated in Norway; in 1954 he emigrated to Canada as a mechanical engineer. There he worked for a while as an architect's aide, but soon joined the Canadian General Electric Company. In 1956, he came to Schenectady in order to follow an advanced training program for engineers. During this period he had one assignment of six months at the General Electric Research Laboratory and worked on a problem of heat flow—a problem in applied mathematics associated with an applied-research project. During this time Giaever noticed that there were solid-state physicists at the Laboratory who were working on problems that seemed to be more interesting to him than the problems of engineering. Near the end of his assignment he asked if he could switch fields and try to become a physicist.

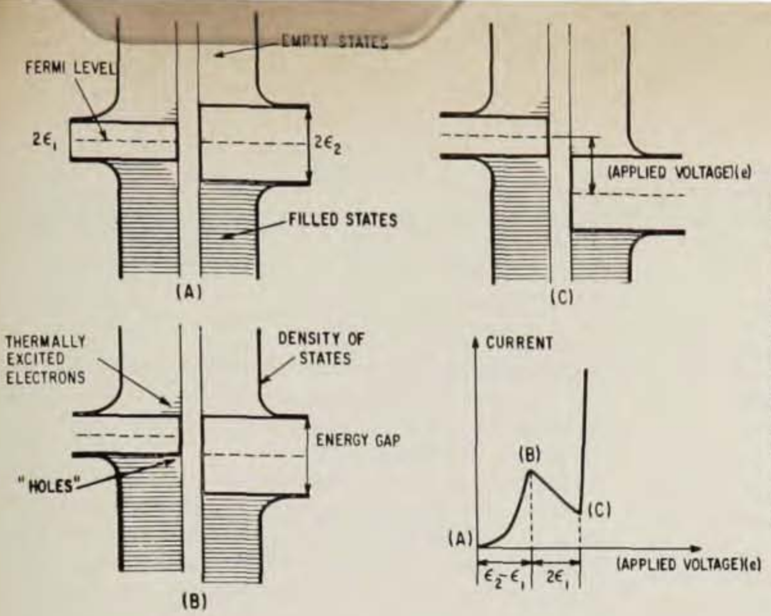
He joined our group, a group devoted to solid-state physics research, in September 1958 and began work under John Fisher. At the same time, Giaever began taking advanced courses in physics at Rensselaer Polytechnic Institute in Troy, N. Y. These studies were to prove critical in the discovery.

Fisher and Giaever began their work on thin films with Langmuir films; they tried, by various techniques, to put metallic electrodes on opposite sides of monomolecular layers and to measure electrical conductance through them. This technique proved so cumbersome and unreliable that after a few months they abandoned it and turned to evaporated-film junctions of aluminum-aluminum oxide-aluminum. With these films they did a series of experiments measuring the relation of electrical current through the oxide film with film thickness, voltage, and temperature, and showed that electron tunneling caused the current through the barriers [4]. During the year occupied with this work, Giaever learned both physics and experimental techniques, and by the end of 1959 he was carrying most of the work forward while Fisher's main efforts remained with other problems; nevertheless, Fisher continued to be the main source of stimulation, ideas, and criticism other than Giaever himself.

Aluminum is a superconductor if cooled below 1.2° K, and it may have been because of this fact alone, and for no better reason, that it was first suggested that the Al-Al_2O_3-Al junctions be cooled to see what effect, if any, superconductivity would have on the tunneling current. The origin of the question, "Why don't you cool them to superconducting temperatures?" is lost; the question is of a type continually being asked in an active research group, and several people asked it at one time or another. Each time Giaever rejected the suggestion, because, he argued, most of the junction resistance was in the barrier itself and a vanishing resistance of the metal films would make no important difference to the junction current. In the light of subsequent events this argument may seem astonishing, yet no one in the preceding decades had joined a conception of the experiment with a reason for doing it, and it is not surprising that Giaever did not at first do so. In any case, he could not at that time have seen the real reason for doing the experiment, for he did not know of the energy gap at the Fermi level in superconductors! He had not, in one year as a physicist, learned all of the things that a person with conventional training would be expected to know, and none of the solid-state physicists among whom he worked had mentioned the superconducting energy gap in a way that had caught his attention.

Early in the spring of 1960, the question about cooling the junctions to superconducting temperatures was asked again, and this time it almost coincided with the study of superconductivity in a course at RPI. There Giaever learned of the energy gap; he recognized that this gap could have an effect on the tunneling current and suggested this possibility to John Fisher, Charles Bean, and Walter Harrison. The first reaction of all three was that probably the gap would not be noticeable. It was, after all, quite small and was only a crude representation of a more complex, many-electron effect; one could not take the simple picture, so like the

Ivar Giaever, Walter Harrison, Charles Bean, John Fisher.



Tunneling between two different superconductors. (**A**) The two superconductors with no voltage applied. Thermally excited electrons above and holes below the gaps are shown. (**B**) When a voltage is applied, the thermally excited electrons in the left superconductor can tunnel into empty levels above the gap of the right superconductor. (**C**) When the voltage is increased further, only the same number of electrons may flow and they now face a lower, less favorable density of states in the right superconductor. The current decreases as a function of voltage until the electrons below the gap of the left superconductor are lifted enough to flow into the levels above the gap of the right superconductor.

picture of a semiconductor, too literally. Nevertheless, they all urged Giaever to try the experiment, and he soon calculated the width of a gap in units one would use in the experiment—in volts. Until then, none of us had noticed (at a time when it would have been meaningful) that superconducting gap widths are in the millivolt range, yet this simple fact was critical at that delicate moment when the experimenter had to decide whether to go ahead or not.

Giaever chose an aluminum-aluminum oxide-lead junction but failed to get definitive results in the first few trials. But, by this time, the conviction that there should be an effect was strong enough to carry the work on, and these efforts were shortly rewarded with success. Within a day or two of this success, Giaever and Charles Bean, who recognized the possible import of the experiment and began to work with Giaever, noticed that a simple model of the electron tunneling allowed them to deduce the density of states near the gap in a superconductor from the shape of the current-voltage curves. This observation suggested that electron-tunneling experiments might yield the density of states near the Fermi energy in normal metals and semimetals. Also, Giaever quickly recognized that tunneling between two superconductors should yield dynamic negative-resistance regions in the voltage-current characteristics. The second of these predictions has proved to be correct, and, following Giaever's publication of the original discovery [1], scientists at Arthur D. Little Company also recognized the possibility, and they, as well as Giaever, proved it to be true [5, 6]. The hope that tunneling experiments could measure the density of states in normal metals and semimetals became dim after detailed theoretical studies of Walter Harrison gave results different from the first, intuitive model. Subsequent experiments have failed to show interesting behavior, but all hope for some effects has not been abandoned.

By now, this discovery has firmly entered the science of superconductivity. It has also broadened the possibilities of other work on tunneling—technological as well as scientific—beyond the realm of semiconductors.

In the end it is not possible to answer the question asked at the beginning of this story: why did this elegant experiment, one that is so easy to do, remain undone during the previous decade? Sir C. G. Darwin has said of the discovery of atomic numbers that it was an "easy" discovery, meaning that "when discovered, it is so easy to understand that it is difficult afterwards to see how people had got on without it" [7]. This kind of discovery, with its birth, destroys unrecognized barriers to the discovery that cannot subsequently be recreated or imagined. In this sense, Giaever's discovery was also an easy one.

Some of the ingredients that led to success are apparent in the story of the discovery: there was a question asked, catalyzing the reaction of knowledge about superconductors with experiments on electron tunneling; there was a delicate balance between theoretical knowledge and naiveté; there was a predisposition for working with simple, uncomplicated equipment; there was the permissive attitude of more senior research people. Chance played a role in arranging these factors, but to no greater extent than it plays a daily role in the research of every scientist; in spite of these ingredients the discovery could have been missed. The final key was that Giaever deliberately tried to make the discovery, and, in the end, knew why he wished to do the experiment and what he was looking for. This fact is probably the crucial fact that caused him to succeed while other scientists in a position to make the discovery did not.

Other discoveries have been made in other ways and the story of this one is not a prescription. But it is a reminder that even in this age of complexity there remain simple, but important, discoveries to be made.

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