Special issue:

Superconductivity

75th anniversary

On countless occasions, I have begun a talk on some aspect of superconductivity by intoning the time-honored sentence "Superconductivity was discovered in 1911 by Heike Kamerlingh Onnes in Leiden, just three years after he had first succeeded in liquefying helium." Accordingly, I could hardly resist the invitation to serve as guest editor of this issue of PHYSICS TODAY, which celebrates the 75th anniversary of that historic event by highlighting some current examples of the broad impact of his discovery.

What Onnes discovered in 1911 was the abrupt and complete disappearance of resistance in certain metals when they are cooled below a critical temperature T_c. This opened the prospect of practical applications such as the production of powerful electromagnets. It was soon discovered, however, that even magnetic fields of less than a kilogauss destroyed the superconductivity of the "soft" superconductors (Pb, Sn and so on) then known. The reason for this was revealed in 1933 by Walter Meissner and R. Ochsenfeld's discovery that such superconductors exclude a magnetic field. Thus the superconducting state is destroyed at a "thermodynamic" critical field H_c, where the energy cost per unit volume $(H_c^2/8\pi)$ of excluding the field exceeds the decrease in free energy of the superconducting state relative to the normal state. In 1935 Fritz and Heinz London proposed two phenomenological equations that neatly described the perfect conductivity and perfect diamagnetism at low fields, but a fundamental understanding of these phenomena eluded all efforts for two more decades.

In the postwar years, the pace of research on this long-outstanding problem increased. In 1950 Vitaly Ginzburg and Lev Landau proposed a profoundly suggestive phenomenological theory of superconductivity as a macroscopic quantum state described by a macroscopic wavefunction ψ. Their theory also introduced the dimensionless parameter κ, which implicitly defined a new length ξ that came to be called the Ginzburg–Landau coherence length; ξ is equal to λ/κ, where λ is the field-penetration depth of the London theory. In 1953 Brian Pippard's insight in interpreting microwave surface-impedance measurements led him to introduce a coherence length ξ_0 measuring the nonlocality of the superconducting electrons; subsequent work made clear the close relationship between Pippard's ξ_0 and the Ginzburg–Landau $\xi(T)$. Other advances in the early 1950s included:

▶ The discovery that the T_c values of many superconductors scaled with isotopic mass as $M^{-1/2}$, suggesting phonon participation in what had appeared to be a purely electronic phenomenon

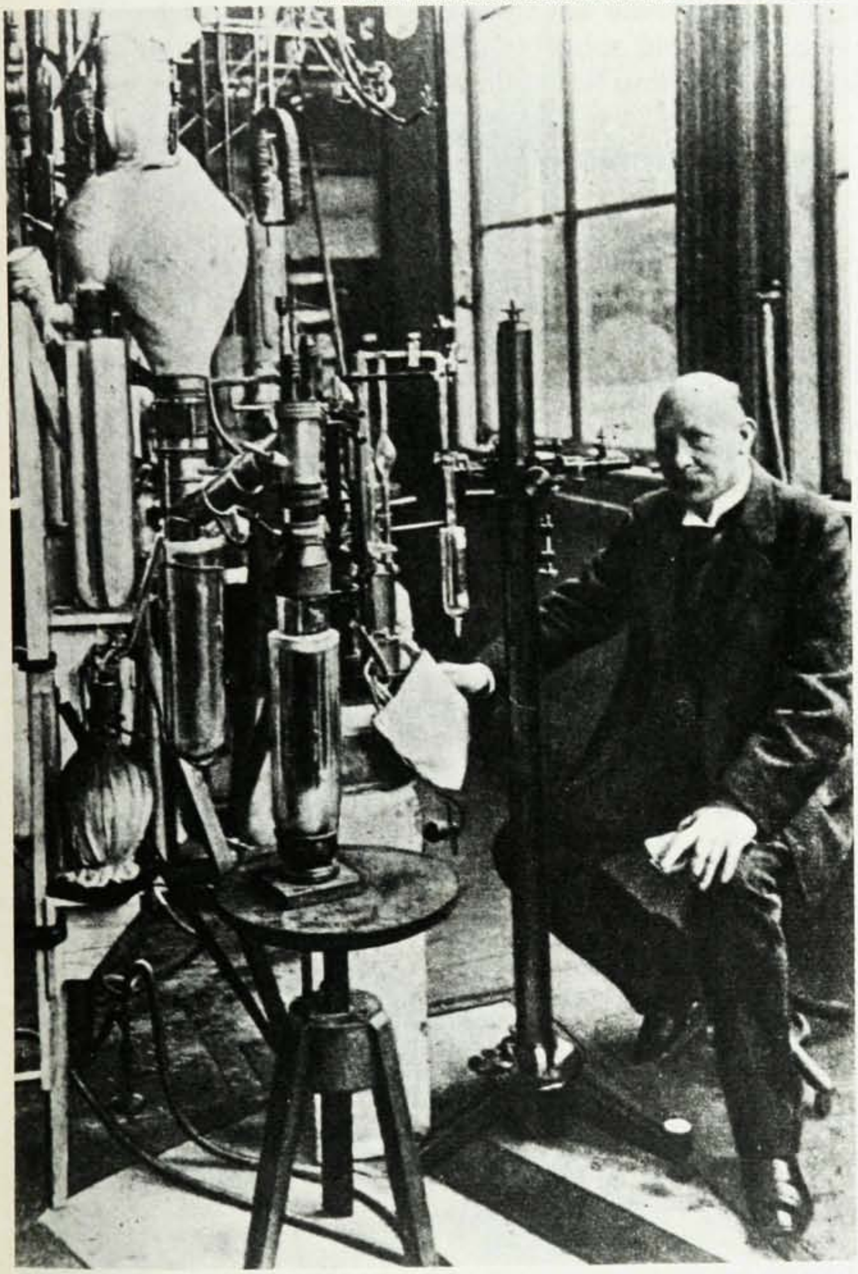
▶ The discovery of an exponential specific heat, which suggested that an energy gap exists in the electronic excitation spectrum, as was soon confirmed by electromagnetic absorption experiments.

These developments reached fruition in 1957 with papers presenting two major breakthroughs: the Bardeen–Cooper–Schrieffer microscopic theory of the superconducting state in terms of "Cooper pairs" of electrons, and the Abrikosov theory of type-II superconductivity. The BCS theory showed how electron–phonon coupling could, at a critical temperature showing the isotope effect, produce a superconducting state with an energy gap Δ of the observed magnitude and with appropriate values for the other measured parameters—H_c, λ and ξ. Two years later, Lev Gorkov showed that the Ginzburg–Landau phenomenology followed from this microscopic theory in the limit of T near T_c. This put the Ginzburg–Landau theory on a firm basis for use in applications. One notable application was the creation of the concept of type-II superconductivity by Alexei Abrikosov. Specifically, he showed that if the GL parameter κ is larger than $1/\sqrt{2}$, a magnetic field exceeding a lower critical field H_{c1} would penetrate the superconductor in a regular array of flux tubes, each confined by a vortex of current and carrying a flux quantum Φ_0 of $h/2e$, or about 2×10^{-15} Wb, whereas for κ below $1/\sqrt{2}$, the Meissner effect of ordinary (type I) superconductors should occur. By greatly reducing the magnetic energy of flux exclusion, type-II superconductors are able to remain superconducting up to an upper critical field $H_{c2}=\sqrt{2}\kappa H_c$, which is greater than H_c and can be very high; this is the basis for the high-field superconducting magnets described in this issue by David Larbalestier and his colleagues (page 24).

This surge of progress culminated in the 1962 prediction by Brian Josephson that a supercurrent proportional to $\sin(\phi_1-\phi_2)$ should flow between two weakly coupled superconductors, where ϕ_1 and ϕ_2 are the phases of the GL wavefunction in the two superconductors, and that this phase difference should increase in time at a rate $2eV_{12}/\hbar$, where V_{12} is the voltage between the two superconductors. This phase difference varies by 2π for each quantum of magnetic flux Φ_0 enclosed

0031-9228 / 86 / 0300 22- 02 / $01.00

RIJKSMUSEUM VOOR DE GESCHIEDENIS DER NATUURWETENSCHAPPEN TE LEIDEN



ONNES

in a superconducting circuit, and this effect forms the basis for the very sensitive superconducting quantum interference device magnetometers described in John Clarke's article (page 36) and also for the superconducting computer described in the article by Hisao Hayakawa (page 46). As Paul Richards discusses on page 54, the Josephson frequency $2eV/h$ is now used to define the standard volt in terms of a precisely measured frequency. In contrast to SQUIDs and Josephson computers, most of the superconductive radiation detectors described in his article are based on the tunneling of "normal" electrons, an effect discovered by Ivar Giaever, rather than on the Cooper pairs of the Josephson effect; for the detectors described by Richards, it is the sharpness of the BCS energy gap Δ that is the crucial aspect of the superconducting state.

The first four articles in this issue outline the status of selected types of applications of superconductivity. Another continuing research frontier is the search for novel types of superconducting materials, which might have better parameters (for example, higher T_c or H_c) or whose behavior might be based on a fundamental coupling mechanism other than the canonical electron–phonon one. By its nature, this search includes many disjoint efforts exploring very different materials. Malcolm Beasley and Theodore Geballe gave an overview of this work in PHYSICS TODAY in October 1984 (page 60) and an article by Richard Greene and Paul Chaikin on organic superconductors is planned for a future issue. To minimize overlap with these articles, the concluding article of this special issue, written by Brian Maple, highlights another class of exotic materials, those in which f electrons play a major role.

It goes without saying that in choosing the fields to be covered in this issue, we had to omit many others in which exciting new work is also going on; the proceedings of the biennial Applied Superconductivity Conferences provide a more complete view of the field. The 1986 ASC, to be held in Baltimore from 28 September to 3 October, will also be recognizing the diamond jubilee that we celebrate in this issue, and will offer participants an opportunity to be brought completely up to date.

MICHAEL TINKHAM
Harvard University