Meetings

Superconductivity

From 26 to 29 August 1963, an International Conference on the Science of Superconductivity was held at Colgate University, Hamilton, New York.

The subject matter was strongly influenced by the recent finding that certain superconductors, called high-field superconductors, are useful in fields up to 100,000 oersteds. Thus, a principal topic of the conference was the type-II superconductor, a species with properties different from those of the familiar type I or soft superconductor. Type-I materials, when cooled below their transition temperature T_c, exclude magnetic flux in all fields up to a critical value H_c. Beyond H_c, flux completely penetrates the sample, normal resistance reappears, and the superconducting state is destroyed. Type-II materials completely exclude flux to a field H_{c1}, but there is a gradual flux penetration thereafter until, at a field H_{c2}, penetration is complete and superconductivity is destroyed. In the region between H_{c1} and H_{c2}, called the mixed state, magnetic flux reversibly enters the type-II superconductor without destroying the superconductivity. Observed values of H_{c2} are as high as 200,000 oersteds, while the largest observed H_c is less than 2000 oersteds.

The physical principles that cause the differences between type-I and type-II superconductivity were reviewed. There is a distance, called the penetration depth, that characterizes the depth in the superconducting phase to which magnetic fields can penetrate and currents can flow. There is another distance, called the coherence distance, that characterizes the distance necessary for a superconducting phase to vanish and a normal phase to appear. If the coherence distance is much greater than the penetration depth, the superconductor is type I; if the reverse is true, the material is type II. The coherence distance and the penetration depth in turn depend on certain normal-state parameters of the material. Using only these normal-state parameters and the critical temperature of the material, physicists, on the basis of phenomenological theories of superconductivity, have predicted H_{c1} and H_{c2}. These predictions agree with the measurements that have been made so far.

Two alternative descriptions of the electromagnetic structure of the mixed state have been proposed. The first, generally favored by most investigators, is an array of flux filaments with cores of nearly normal material. The second is an array of flux lamellae. As was pointed out at the conference, there have been no definitive experiments to determine which description is correct; careful experiments defining the structure of the mixed state are needed.

In a simple, pure type-II superconductor, uncomplicated by the influence of imperfections, the flux filaments would be expected to form some sort of regular structure. It was proposed that cold neutrons could be used to determine this two-dimensional structure. It was also proposed that these flux filaments, by virtue of their mutual repulsion and their inertial properties, ought to have collective excitational modes.

The simple magnetic properties of type-II superconductors change dramatically under the influence of imperfections; these superconductors are much more sensitive to defects than are type-I materials. The effect of precipitate particles is delineated particularly well, as it has been possible to make a series of experiments in which the pertinent variables could be altered one at a time. Large magnetic hysteresis presumably occurs because imperfections in the material impede the motion of flux filaments, permitting large spatial variations in the number density of filaments and thus large superconducting currents. The motion of flux filaments through material containing defects was the subject of theoretical as well as experimental study. It is postulated that the fundamental process is the thermally activated motion of bundles of flux filaments. The phenomenon of "flux creep," the slow passage of flux through a region of faulted type-II material, is predicted and has been observed. However, as the flux filaments have not yet been directly detected, their interaction with lattice imperfections is known only indirectly and speculatively.

Fortunately, a rather simple phenomenological theory is applicable to magnetic hysteresis and current flow in high-field superconductors. The basic physical assumption is that the distribution of fields and currents in a high-field material is such that there is a limiting current density flowing wherever the current has been previously induced by a changing field. This assumption can be rationalized on the basis of the pinning of flux filaments by defects in a type-II material. This simple theory yields analytical expressions for the magnetic hysteresis of high-field superconductors which have shown excellent agreement with experiment. The variation of this limiting critical current density with magnetic field is sensitive to structure; the precise dependence of this characteristic on the composition and structural parameters of high-field materials was discussed.

Another, quite different, structure of superconducting material that is associated with a high critical field is an interconnected mesh of tiny superconducting filaments in a nonsuperconducting matrix. (The flux filaments, by contrast, are filaments of very nearly normal material, containing flux, in an otherwise superconducting material.) In several cases it appears that a diminished resistivity persists at fields above H_c in type-I superconductors, or above H_{c2} in type-II superconductors. It may be that the fine superconducting filaments are responsible for the observed reduced resistivity. Some workers have suggested that these filaments carry the high critical currents in the mixed state, though most attribute the mixed-state critical currents to the defect-stabilized flux filaments. Clear examples of high-field superconductors of the mesh class are those made synthetically by pressing ordinary type-I materials into unfired Vycor glass, a material in which interconnected pores as small as 40 angstroms in diameter comprise about 30 percent of the volume.

Another major topic of the conference, the work on transition elements and alloys, is germane to at least two fundamental problems of superconductivity: (i) Which of all the known elements, alloys, and compounds will be superconducting? (ii) What interactions between electrons cause superconductivity?

As more than 75 percent of the transition elements are known to become ordered at low temperatures, either magnetically or by becoming superconductive, it is conjectured that this may be true of all of them. Failure to observe superconductive or magnetic ordering is not conclusive proof that neither occurs, for very small amounts of magnetic impurity seem to quench the superconductivity of elements that are only weakly superconductive. An experimental approach that has been fruitful is that of searching for superconductivity among alloys and compounds of the transition elements and, on finding it, observing the effect of composition on transition temperatures. Such results may yield circumstantial evidence for the occurrence of superconductivity in one of the parent elements; by such means the superconductivity of molybdenum and iridium was discovered.

One interaction that causes superconductivity is a phonon-mediated interaction between electrons. Is this the only interaction causing superconductivity? Two lines of experimental work have been adduced to support the view that it is not: (i) the effect of isotopic mass on the transition temperature is absent in ruthenium and very small in osmium, and (ii) superconductivity in some transition elements or alloys is enhanced by the addition of magnetically active elements; for example, there is an increase in the transition temperature of titanium when iron is added. However, theoretical developments have shown that the isotope effect can be abnormally small in transition elements even when the phonon-mediated electron interaction is the only one operative. Also, because small additions of iron to titanium appear to have an effect on the crystal structure of titanium, the precise effect of iron on the transition temperature of titanium is in doubt. Unfortunately, only circumstantial evidence can be given for the existence of interactions other than the phonon-mediated one, because no such interaction has been given in sufficient detail to make a critical prediction. Therefore, although further suggestive experimental work was reported—variation of T_c with composition in the ruthenium-osmium system; the effect of iron, ruthenium, or osmium on the T_c of niobium—the existence of other than a phonon-mediated interaction is not at all clear.

The effect of superconductivity on the tunneling of electrons through a thin insulating layer between two metals was discovered in 1960. Since then, the phenomenon has become a major tool in superconductivity research. It was first used to measure the energy gap in the electron energy spectrum of superconductors and to measure the density of electron states at energies near the gap. There are now three main lines of work on electron tunneling between superconductors. First, detailed measurements of the variation of current with voltage reveal a structure that is attributable to the phonon spectrum; this structure is emphatically displayed by the second derivative of current with respect to voltage. Peaks in this quantity occur at energies equal to those of the highest density of transverse and longitudinal phonons, and less pronounced fine structure corresponds to certain other critical points in the phonon spectrum. It is a bit surprising that the electron tunneling experiments reveal as much as they do about the phonon spectra of superconductors.

The second main line of research on electron tunneling is on multiple-particle tunneling in which two unpaired electrons cross the barrier together. These tunneling currents flow at voltages of less than the gap voltage, thereby augmenting the currents due to thermally-excited, single electrons. However, it appears that single-particle tunneling is sometimes prompted by the direct involvement of a phonon, and this process may also contribute to the augmented current.

The most interesting new studies of tunneling are those of the "Josephson effect," named after the Cambridge student who recently predicted its existence theoretically. He said that tunneling current can flow by the transfer of condensed pairs across the barrier, even when no voltage is applied to the tunnel junction. Experiments have proved that this current exists by showing that it has the predicted sensitivity to, and periodicity in, an applied magnetic field. A second aspect of the Josephson effect is an oscillating supercurrent through the junction when a voltage is impressed on it; the frequency should be proportional to the applied voltage. Some of the effects predicted for the exposure of such an oscillating junction to radiation of the same frequency have been observed. Further developments are certain to occur in this fascinating and rapidly developing field.

A most puzzling problem of superconductivity has been that of the Knight shift, the change in the frequency of the nuclear magnetic resonance of an atom when the atom is in a metal rather than an insulator. In nontransition metals this shift is due to the modification at the nucleus of an externally applied field by the spin paramagnetism of the *s*-conduction electrons. The spin paramagnetism of these electrons is expected to go to zero in the superconducting state as the temperature approaches 0°K, for the electrons in the superconducting ground state are supposed to be paired with opposite spins. Thus, the Knight shift should go to zero at 0°K; measurements made to date in nontransition metals do not show the expected vanishing Knight shift. Partial destruction of the spin pairing through a strong spin-orbit coupling has been suggested as an explanation for this discrepancy. It would be premature at this time to judge the validity of this idea.

In transition metals and their compounds there are two additional contributions to the Knight shift: the orbital magnetism of the unfilled shells of *d*-electrons and the polarization of ion core *s*-electrons through interaction with the spin polarization of the *d*-electrons. The orbital magnetism presumably does not change in the superconducting state. Sorting out these contributions is quite tricky; the investigators who did so for V_3Ga and V_3Si concluded that the spin pairing was very nearly that expected by theory, while those who looked at vanadium metal concluded that the spin pairing was even less than that observed in the nontransition metals!

Magnetic flux through a region enclosed by material in the superconducting state is quantized. This important fact, anticipated by F. London in 1950, was discovered in 1961 from careful measurements of the magnetization of tiny superconducting, cylindrical shells. Because the quantum value is small, only 2×10^{-7} gauss per square centimeter, quantization can often be neglected, but it plays an important role in several phenomena. The flux filaments postulated in the electromagnetic structure of type-II superconductors are thought to contain one flux quantum each. However, as noted earlier, these filaments have not been detected by any method that could be considered reasonably direct. Also, it is believed that flux filaments are the unit of electromagnetic structure when a magnetic field is applied perpendicular to the plane of a thin superconducting film, even though the film is of type-I material.

Just as for bulk type-II materials, the flux-filament model leads to correct predictions of the properties of films, such as the upper critical field and its angular dependence. These results inspired an attempt to get more direct evidence for the existence of quantized flux filaments. The resistance of a thin film was measured as a function of magnetic field perpendicular to the plane of the film, the film being so narrow ($\sim$ 1 micron) that its physical dimension would determine the size of the flux filament. It was argued that minima in the resistance measurements should occur at values of the magnetic field that would make one flux quantum thread an area determined by the width of the film; minima were seen at about the expected values of H.

The cylinders in which flux quantization may be observed are a few microns in diameter; persistent currents are observed in samples as large as several centimeters. Thus a form of order, the phase coherence of the superconducting wave function, persists over distances much longer than the coherence length mentioned earlier. This long-range order was discussed at length, the fundamental question being its universality. Long-range order and thus flux quantization exist in some materials. Do they in all? In one preliminary experiment with vanadium cylinders there seemed to be no flux quantization.

The conference, attended by 350 scientists from 11 countries, was sponsored by the International Union of Pure and Applied Physics, the National Science Foundation, the Advanced Research Projects Agency, and the General Electric Research Laboratory. The conference proceedings are to be published in the January 1964 issue of *Reviews of Modern Physics*.

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Forthcoming Events

January

20–22. American Inst. of **Aeronautics and Astronautics,** aerospace sciences meeting, New York, N.Y. (R. R. Dexter, AIAA, 2 E. 64 St., New York 21)

20–23. **Cardiovascular Drug Therapy.** symp., Philadelphia, Pa. (S. Rosen, Dept. of Medicine, Hahnemann Medical College and Hospital, 230 N. Broad St., Philadelphia 2)

20–24. **American Mathematical Soc.,** Miami, Fla. (AMS, 190 Hope St., Providence 6, R.I.)

20–24. **Australian and New Zealand Assoc. for the Advancement of Science,** Canberra (J. R. A. MacMillan, Faculty of Agriculture, Univ. of Sydney, N.S.W., Australia)

20–27. **Agricultural Film Competition,** 3rd intern., Berlin, Germany. (Congress Hall, John Foster Dulles Allee, Berlin N.W. 21)

22–25. **American Physical Soc.,** New York, N.Y. (APS, Columbia Univ,, New York, N.Y.)

22–25. American Assoc. of **Physics Teachers**, New York, N.Y. (E. U. Condon, Oberlin College, Oberlin, Ohio)

23. Central Council for **Health Education**, annual conf., London, England. (Director, CCHE, Tavistock House, Tavistock Sq., London, W.C.1)

23–24. **Industrial Water and Waste** Conf., Austin, Tex. (J. B. Maline, Jr., 305 Engineering Laboratories Bldg., Univ. of Texas, Austin 12)

25. **Industrial Hygiene** and Air Pollution, 8th conf., Austin, Tex. (J. O. Ledbetter, 305 Engineering Laboratories Bldg., Univ. of Texas, Austin 12)

27–30. Society of **Plastics Engineers,** 20th annual technical conf., Atlantic City, N.J. (J. J. McGraw, Natl. Vulcanized Fibre Co., Philadelphia, Pa.)

27–31. UNESCO, working party on **scientific translation and terminology,** Rome, Italy. (UNESCO, Place de Fontenoy, Paris 7)

28–30. **Entomological** Soc. of America, southeastern branch, Asheville, N.C. (W. C. Nettles, Clemson College, Clemson, S.C. 29631)

29–31. American **Meteorological** Soc., 44th annual, Los Angeles, Calif. (A. Court, 17168 Septo St., Northridge, Calif.)

29–1. Southwestern Federation of **Geological Societies,** 6th annual, Midland, Tex. (W. E. Wadsworth, AAPG, 1444 S. Boulder, P.O. Box 979, Tulsa 1, Okla.)

29–1. Western Soc. for **Clinical Research,** 17th annual, Carmel-by-the-Sea, Calif. (H. R. Warner, Latter-Day Saints Hospital, 325 Eighth Ave., Salt Lake City, Utah)

30–31. Spontaneous and Experimental Comparative **Atherosclerosis**, conf., Beverly Hills, Calif. (E. McCandless, Los Angeles County Heart Assoc., Los Angeles 57, Calif.)

February

2–5. American Inst. of **Chemical Engineers**, annual, Boston, Mass. (J. Henry, AICE, 345 E. 47 St., New York, N.Y.)

2–7. Institute of **Electrical and Electronics Engineers**, winter meeting, New York, N.Y. (A. P. Fughill, Detroit Edison