# SUPERCONDUCTIVITY

## *Colloquium at Cambridge, England*

## *June 30—July 3, 1959*

*A Report by* ***E. A. Lynton***

FOR three and one half days, some seventy physicists from many countries (unfortunately not including the U.S.S.R.) met at Cambridge to discuss the present theoretical and experimental status of superconductivity. From every point of view it was a nearly ideal conference. As the entire meeting was devoted to a restricted subject, there were single sessions which were most interestingly organized: a rapporteur summarized a certain area in about 45 minutes, after which there was an equal time for discussion. This system eliminated the presentation of a tedious number of short contributions and, thanks to the devoted efforts of the rapporteurs, made much clearer the basic questions involved. And then there was the wonderful setting of Cambridge, and the warm hospitality of the hosts, who made all participants feel at home from the moment when they were welcomed in person by Dr. Shoenberg as they arrived, one by one, at Clare College. No effort was spared in organizing all aspects of the scientific program, and in adding to it a most enjoyable social round. There was punting on the Backs and tea at Grantchester (without honey), excursions to stately homes, a much appreciated recital by Messrs. Gough (violin) and Pippard (piano), and, as penultimate joy, a speechless banquet. The smoothness with which everything proceeded belied the extraordinary amount of preparation done by the Shoenbergs and the Pippards, by Faber, and by the other members of the Mond Laboratory; may they be assured that their efforts were unqualifiedly successful.

The one shadow on this otherwise so pleasant meeting was cast by the announcement of the shocking accidental death of Robert Schafroth. To have known him was to have liked him, such was the warmth and charm of his personality, and his memory will be cherished by his many friends.

So much did everyone enjoy the conference that all would welcome a repetition a year or two hence (of course with the same hosts)—but regretfully it must be said that in all probability this has been the last meeting fully devoted to superconductivity. Both in theory and in experiment much work remains to be done in this field, and valuable contributions will be needed and will be made for many years to come. But it is now generally agreed that our understanding of the phenomenon of superconductivity in terms of the Bardeen, Cooper, and Schrieffer theory is such as to remove it from the shrinking list of major unsolved problems. There is much similarity now to the state of affairs in the theory of metals: in both cases the basic mechanisms are recognized and can be described to a good degree of approximation in surprisingly simple terms, in both cases there is no real proof (but also no real doubt) that one is dealing with the true ground state, in both cases a major analytical advance is needed for a rigorous derivation from first principles and for precise calculations of quantitative details.

THIS very encouraging general situation was clearly established in the three sessions of the first day of the conference, during which the theoretical picture was presented by Bardeen (Illinois), by Anderson (Bell Laboratories), and by Wentzel (Chicago).

Bardeen feels that the principal shortcoming of the present theory is its inadequate account of the Coulomb interaction, which should be improved by a more careful treatment of the quasi-particle lifetimes. This would probably lead to different phonon cut-off fre-

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quencies for different superconductors and, therefore, explain the empirical variations of the energy gap width for different elements. The further leading problems at this moment according to Bardeen are:

(a) An explanation of the apparently nonvanishing electron spin paramagnetism in superconductors at 0°K, as shown by the Knight shift.

(b) A calculation from first principles of the interphase boundary energy between the superconducting and the normal phase, to supplement the phenomenological treatment of Landau and Ginsberg.

(c) A more careful treatment of electron-phonon scattering, both as applied to ultrasonic attenuation in the case of short electron mean free paths, and also to thermal conductivity.

(d) A calculation of the nonlinear terms in high field effects.

(e) A better understanding of thin films and small particles.

(f) A more detailed treatment of collective excitations.

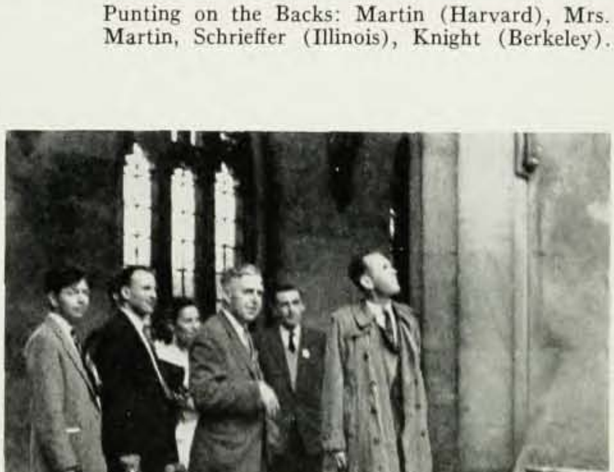
Anderson discussed the place of superconductivity in the general context of the many-fermion problem. The BCS and equivalent theories treat superconductivity in the weak coupling limit of an attractive interaction involving both a potential and a phonon field. There is no real proof that the lowest state obtained is really the ground state without using possibly nonconverging perturbation methods. But the same is true of the weak coupling limit of the repulsive interaction, namely the Fermi sea, of which the sharp drop in density of states is really on the face of it much more unstable. In both cases one firmly believes that the present descriptions are correct, but much fundamental work is needed. Much effort should also be devoted to investigating carefully the transition from the weak to the strong coupling limit.

During the subsequent discussion Wentzel pointed out that the question of the true ground state in both weak interaction limits is really a question of the range of validity of the random phase approximation. Pines (Illinois) enlarged on the interrelation between a better understanding of the Fermi sea and a better criterion for superconductivity, and suggested that the two problems are soluble together. In the present theory of metals one obtains a sharp Fermi surface by treating the interaction of a single excited electron with all the sea, neglecting its interaction with the other excited electrons. In superconductivity one treats the interaction of electrons within a thin shell near the Fermi surface and essentially neglects that with all the rest of the sea.

In his report Wentzel outlined the presently very satisfactory state of the Meissner effect and of gauge invariance in superconductor theory. This has been achieved by taking into account the collective excitations (plasmons) as had first been suggested by Bardeen and worked out by Anderson. Further con-

In the garden of an Elizabethan estate: (left to right) Webber (ONR, London), Mendelssohn (Oxford), Serin (Rutgers) and Miss Serin, Anderson (Bell Labs), Pines (Illinois), Abrahams (Rutgers), Mrs. Nozieres, Redfield (IBM Watson Lab), and Nozieres (ENS, Paris).

Punting on the Backs: Martin (Harvard), Mrs. Martin, Schrieffer (Illinois), Knight (Berkeley).



Touring the colleges: Sewell (Liverpool), the Nozieres, Shoenberg (Cambridge), Dupre (Louvain), Abrahams.

tributions to this problem, in addition to that by Pines and Schrieffer, have recently been made both by Rickayzen and by Bogoliubov. In spite of the great difference of mathematical detail of these last two treatments, they are essentially equivalent.

AFTER this first day of theoretical discussion, the remainder of the conference was devoted to seeing (to quote Shoenberg) whether the experiments fit the facts. Pippard began by showing that on the whole such a fit exists in the interaction of superconductors with electromagnetic radiation of moderate frequencies. There is some question about the temperature dependence of the penetration depth in impure samples, and there is an unexplained variation between the field dependence of the penetration depth of 3-cm waves measured by Pippard, and of 30-cm waves investigated by Mrs. Dresselhaus. But there is no longer any evidence for a nontensorial behavior of the penetration depth in anisotropic samples, and the excellent agreement of the measured surface impedance very near $T_c$ with theoretical prediction has led Pippard to abandon his belief in a temperature dependent range of coherence.

A similarly satisfactory state of affairs exists in very high frequency experiments. Tinkham (Berkeley) pointed out that both the work of the Westinghouse group with microwaves and his own with far infrared show an energy gap of magnitude and temperature variation essentially as predicted by the BCS theory. There is clear evidence that the size of the gap at $0°$K (in terms of $kT_c$) varies from one element to another, and some indication that this size is correlated with the reciprocal of the Debye temperature. The infrared results also show in some elements a certain structure of the absorption edge, which most people ascribe to the presence of multiple pair correlations (excitons) of energy less than single particle excitations, as had been discussed by Anderson.

Goodman (Grenoble) then summarized the thermal properties of superconductors, particularly the specific heat, from which the presence and magnitude of an energy gap can also be clearly inferred. On the whole there is good agreement between calorimetric and high-frequency results, except in the case of niobium. At the lowest temperatures a logarithmic plot of the electronic specific heat of aluminum and of zinc deviates upward from the values predicted by the BCS theory on the basis of a uniform energy gap. This is a strong indication of the anisotropy of the gap in these elements.

Satterthwaite (Westinghouse) put much order into the confused state of the field of thermal conductivity in superconductors. Of the two thermal carriers—phonons and electrons—each has one scattering mechanism for which theory and experiment agree, and one for which there is much confusion. The heat conduction by phonons at the lowest temperatures is expected to be limited by boundary scattering and to vary as the third power of the temperature, and this is well substantiated experimentally. But when one extrapolates this to higher temperatures and attempts to obtain that part of phonon conduction which is limited by electronic scattering, confusion arises because the electronic scatterers are themselves also carriers of heat. As a result, estimates of this part of the phonon conduction are very unreliable, and disagreement with theoretical predictions not surprising. The situation with regard to the electronic conduction as limited by phonon scattering is equally unsatisfactory, although here the experimental data are probably more reliable than the theoretical calculations. The results with highly pure lead and mercury both show a very abrupt decrease of the conductivity at $T_c$, whereas very recent calculations of the Illinois group predict a rise of the conductivity in the superconductive state over that in the normal one.

The agreement between experiment and theory in the region of impurity limited electronic conduction is on the whole very good, minor differences between, e.g., zinc and aluminum being probably due to energy gaps of different magnitudes.

The situation with regard to the interphase boundary energy was summarized by Faber (Cambridge). There is quite reasonable agreement between the experimental values obtained by different methods (propagation of the interphase boundary, powder patterns, restoration of thin film resistance, and supercooling). These values also agree with the predictions of the phenomenological theory of Landau and Ginsberg, especially as recently improved by Ghorkov. There is, however, as yet no way of deriving this boundary energy from the BCS theory.

Serin (Rutgers) discussed the effects of both nonmagnetic and magnetic impurities. The mean-free-path effect of nonmagnetic impurities on $T_c$, established by the Rutgers group, has been verified in other laboratories and has been treated theoretically both by Anderson and by Abrahams and Weiss. The latter proceed in the spirit of the BCS theory by calculating the effect of impurity scattering on the interaction matrix elements averaged over an isotropic energy gap. Anderson, on the other hand, considers it essential to start with an anisotropic gap in the ideally pure metal, and believes that the principal effect of impurity scattering is a smoothing out of this anisotropy, leading to a lowering of $T_c$.

The situation regarding magnetic impurities is very confused. In ternary mixtures investigated by Matthias and others at Bell the smoothly and fairly slowly varying plot of $T_c$ versus magnetic concentration intersects the similarly smooth curve of Curie points. For concentrations past this intersection there is some indication of a simultaneous occurrence of superconductivity and ferromagnetism. In his earlier report, however, Anderson mentioned his doubts about this, and pointed out that the crucial concept of a nonlocal susceptibility in superconductors can lead to a cryptoferromagnetic state with small domains aligned such that the average magnetization vanishes.

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The theme of microelectronics is that if you want environment-immune, highly "intelligent" circuitry that can handle problems of logic and fit into a tenth of a cubic inch of space or so, you quit at an early stage of the design thinking of transistors, diodes, capacitors, resistors, and such. Instead you think of the circuit as one or more plates half a millimeter thick and fabricated as intricately as necessary out of various conductive, semi-conductive, and dielectric materials disposed among the three dimensions of each plate.

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In the binary compounds investigated jointly by the Bell and the NRL groups, the variation of $T_c$ with concentration is almost discontinuous in the crucial region of possible overlap, and there is no clear evidence of the simultaneous occurrence of superconductivity and ferromagnetism in the same sample.

THE last day's sessions were opened by Knight (Berkeley) speaking appropriately enough about the shift in nuclear resonance frequency which bears his name. His recent measurements of this shift in superconducting tin are very similar to earlier results of Reif on mercury, and definitely point to a finite value of the Knight shift at 0°K. The single earlier result of Knight which implied a vanishing of the shift at the lowest temperatures is no longer considered reliable. Clearly the existence of a finite electron spin paramagnetism at 0°K seems to be quite at variance with the electron pairs of opposite spins crucial to the BCS theory, and this is one of the most important questions to be cleared up by further theoretical work.

Knight also summarized various measurements of nuclear spin relaxation times in superconductors, all of which yield the crucial result of an enhancement of the relaxation just below $T_c$. This indicates unequivocally the existence of an energy gap with the "missing" states piled up on either side, and is in excellent quantitative agreement with the BCS theory.

Morse (Brown) concluded the conference with an account of his investigations of ultrasonic attenuation in superconductors, particularly his very recent measurements on variously oriented single crystals of tin. The ratio of attenuation in the superconductive to that in the normal phase decreases very rapidly with decreasing temperature, in good agreement with the theory, and the variation of this ratio in the low-temperature limit yields a value of the energy gap. In this fashion Morse finds differences of 10 to 20 percent in the gaps in different crystal directions of tin. While there is perhaps some doubt about the numerical value of this gap anisotropy, these experiments appear to leave little doubt about its existence.

During this session Bömmel (Bell Laboratories) gave a brief account of his present use of "hypersound" with frequencies ranging perhaps as high as 100 000 Mc/sec. Very preliminary results of the change of attenuation at $T_c$ at a frequency of 30 000 Mc/sec (corresponding to phonon energies of about 0.5 $kT_c$) indicate an initial rise of attenuation in the superconductive state, for which there is as yet no theoretical explanation.

This brief account of the various sessions of the most recent Colloquium on Superconductivity will have indicated that much work remains to be done even within the present theoretical frame, and many experiments must still be done or improved. Perhaps this will, after all, provide sufficient reason for another meeting like the one described here—or if not a reason at least an excuse to gather again as pleasantly, congenially, and instructively as was done this time.