

Low Temperature Conference

a report by J. Wilks



THE department of physics at the University of Wisconsin, Madison, Wisconsin, was host to the Fifth International Conference on Low-Temperature Physics and Chemistry from August 26 to 31, 1957. The National Science Foundation, Office of Naval Research, Atomic Energy Commission, International Union of Pure and Applied Physics, and the Wisconsin Alumni Research Foundation joined with the University of Wisconsin in sponsoring this conference. 440 scientists attended with 353 coming from the United States, 24 from Canada, and a total of 63 from the following 11 countries: Australia, Belgium, Finland, France, Germany, Great Britain, Holland, Italy, Japan, Norway, and Switzerland.

Twenty-five years ago the production of liquid helium was itself a considerable achievement and a passport to a remote and strange region. The number of people working there was correspondingly small, and they were well acquainted with all the experiments being done at helium temperatures. Today the advantages to be reaped by working at low temperatures have been exploited in almost every branch of physics, thanks not least to the Collins helium liquefier manufactured by A. D. Little, Inc. Even in what appeared to be a last stronghold of resistance, nuclear physics, the recent experiment on parity at the National Bureau of Standards has underlined the importance of nuclear orientation, one of the most refined and difficult low-temperature techniques.

From the reports of research at the conference it was apparent that a great deal is happening at low temperatures. It was necessary to run as many as three sessions concurrently in order to accommodate the 198 contributed papers at the conference. The 27 invited papers and 2 special lectures were given at general sessions. Although it was not possible for one to hear all of the contributed papers, judicious choices of topics to be covered in concurrent sessions, when the program was arranged, made it possible for those with special interests to hear the papers of most concern to them. To be able to do this and in addition have the opportunity of listening to some papers and discussions in related fields gave an excellent example of the importance of such a large meeting. The material on liquid

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helium alone would have kept the conference fully occupied. Superconductivity was well represented, and there were many papers on work below 1°K which still retains much of the pioneer character that the helium region had before the war. The other topics were less clearly grouped but included thermal properties, electrical and thermal conductivities, mechanical properties, and magnetism. The following account is an impression of some of the papers which either caught the imagination of the conference or appeared to be significant for the future. In preparing it the author is indebted to those colleagues who, at Madison or after, have told him of talks he did not hear or did not understand. The proceedings of the conference are being published by the University of Wisconsin Press.

BESIDES making all other experiments possible liquid helium was much discussed for its own sake. It is now recognized that the behavior of liquid He^4 below the lambda point (helium II) is substantially modified if it is carrying high heat currents or flowing quickly. For small heat flows, the heat current in a capillary of liquid helium is proportional to the temperature gradient, but for higher heat flows becomes proportional to the cube root of the temperature gradient; alternatively, if the helium is vigorously stirred the heat flow is much reduced. The theory of the initial linear region was first given by Landau, and was amplified by Feynman a few years ago. At the Conference at the Rice Institute, Houston, Texas, in 1953, Landau's treatment was still under discussion, but at Madison nearly everybody made the tacit assumption that it is substantially correct.

At first sight the Landau theory appears rather strange, but it is in fact no stranger than the observed properties of the liquid. Above the lambda point we

may think of liquid helium as a collection of helium atoms each like a rather small billiard ball. If the liquid flows through a narrow tube the atoms (billiard balls) collide with the walls and with each other, and there is a viscous resistance to flow. However, below the lambda point some atoms flow through the tube without experiencing any resistance at all, and the question is how do they avoid hitting the walls and the other atoms? As in many other problems solved by wave mechanics, the answer is that atoms are not billiard balls and one must not think of them as such, especially at low temperatures where quantum effects become important. The conceptual difficulties are no greater (but also no less) than we experience in explaining how particle-like electrons produce a diffraction pattern. In the case of He^4 , however, there is the important proviso that the wave functions used are not those of individual atoms, but of the whole assembly of the liquid. Feynman's treatment is a little unusual and makes use of the angular correlation function for the liquid which can in principle be calculated but in fact is determined from experiment. Therefore, some interesting attempts were made to derive the same essential picture by starting from a gas of helium atoms obeying Bose-Einstein statistics and then introducing interactions so as to form a liquid. It is not yet entirely clear how rigorous these methods are, nor if such treatments are a necessary adjunct to Feynman's approach.

Landau's theory leads to the conclusion that liquid helium at absolute zero cannot be set into rotation, and several experiments have been performed at finite temperatures which appear to verify this prediction. However, Hall has recently shown that if a vessel containing liquid helium is rotated for several minutes, all the liquid is eventually set into rotation. The helium in this rotational state does not transmit heat so well (as mentioned above), and it is convenient to refer to the rotating helium as being in a state of "turbulence" without committing ourselves too closely as to the exact meaning of this term. The theoretical problem is to find some wave function to describe this condition and H. London and Onsager have suggested that the ground state of rotating helium will consist of zones of liquid in the true irrotational ground state separated by sheets or grids of vortices. According to Feynman the vortices will be quite large, even large enough to be detectable on a macroscopic scale, and two experiments were reported which aimed at detecting the creation of a single vortex. Vinen described an experiment in which liquid helium was confined in the space between two concentric cylinders of which the inner cylinder was a fine wire which could be vibrated electromagnetically. The theory predicts that on rotating the outer cylinder a vortex should form at a certain velocity and affect the resonance frequency of the wire. Pellam had looked for a similar effect by measuring the lift due to superfluid helium flowing over an aero foil, as theory predicts that the lift should be zero in the absence of vortices but should change discontinuously to a quantized value when a vortex is formed. (The first aero foils tried con-

sisted of flies' wings and the forces were measured in millidynes!) Both these experiments gave negative results in agreement with each other, but not with the theory, and clearly quite a lot of work remains to be done.

He^3 is of course much rarer than He^4 , and 1 cc of liquid is still a comparatively large quantity. However, the volume of work on it is increasing rapidly, and at Madison the number of experiments described was comparable to that on He^4 . Although He^3 remains liquid to the lowest temperatures its properties are not as remarkable as those of helium II; it is not superfluid nor does it show a high heat transport, and there is general agreement that this is because it obeys Fermi statistics whereas He^4 obeys Bose statistics.

The nuclear spin of He^3 gives rise to a nuclear magnetic susceptibility and W. M. Fairbank showed some time ago that Curie's law is obeyed down to about 1.0°K when some alignment of the spins appears to set in. If the liquid behaved like a Fermi gas this behavior would imply a degeneracy temperature of about 0.5°K, rather than the temperature of 5°K that one would calculate from the liquid density and atomic mass. The specific heat above about 1°K is approximately linear with temperature, like that of a degenerate Fermi gas, but shows very poor agreement with either degeneracy temperature. In view of these discrepancies it is obviously hopeless to try to produce a theory of the liquid in terms of a dense gas, and until very recently discussions of the liquid were held up at this point. However, Brueckner presented a very interesting paper showing that the main properties of the liquid might be derived by techniques previously applied to the liquid-drop model of the nucleus. In essence, this treatment starts with the wave functions of a perfect gas and proceeds by finding transformation functions which will correspond to the switching on of the interactions which exist in the liquid. The theory does not lead to explicit expressions for the various thermodynamic properties of liquid helium-3 and these have to be calculated on a large computer. Although full and exact agreement is not yet obtained, the results are sufficiently promising to suggest that the basic approach of the theory is correct.

Solid He^3 also received much attention as it appears to be a more complex solid than He^4 , and the chief topic of interest was when and how the nuclear magnetic moments become aligned. Alignment in the liquid sets in at temperatures of about 1°K and is presumably brought about by exchange forces. It has been argued that in the solid state the wave functions will be more localized, so that exchange or magnetic forces will only produce alignment at much lower temperatures. However, W. M. Fairbank reported measurements which showed that the behavior of the solid was not vastly different from that of the liquid, and alignment of the spins appeared to begin at about 0.2°. This situation is still of great interest as there is a region in which the spins are more aligned in the liquid, than in the solid, so that the solid probably has the greater entropy.

Apart from this work, Mills and Grilly had investigated the melting curve and found a transition in the solid, which on the melting curve occurs at a pressure of about 150 atmos. This result recalls the transition in solid He^4 from a cubic to a hexagonal close-packed lattice, but the volume and energy changes in He^3 are considerably larger than in He^4 . Thus, the solid does not behave quite as expected and there is still much to look at.

Before leaving helium one must also refer to what was perhaps the most important item of the whole conference; namely, the supply of helium gas on which nearly all of low-temperature physics depends. The consumption of helium by cryogenics, by industrial welding, and by large balloons, is rising rapidly. Professor Collins has made a survey of the position and came to the conclusion that if things continue at the present rate of development, the wells of helium-bearing gas may be exhausted within 10 or 15 years. However, at present only a small part of the helium-bearing gases are passed through the separating plants and much more helium could be obtained without detriment to the other gases. Clearly, the matter is urgent and at the suggestion of Dr. Brickwedde a resolution was passed calling on the US Government to take speedy and appropriate action.

The conference heard of much new work, theoretical and experimental, on the basic question of how superconductivity arises. In 1951 experiments showed that any theory of superconductivity must take account of interactions between the electrons and the lattice, because the transition temperature was different in different isotopes of the same metal. (That is, in metals differing only in the mass of the lattice ions.) At about the same time both Bardeen and Frohlich produced theoretical treatments taking such effects into account, but it was not possible to obtain many quantitative results. Although a considerable number of useful experiments have since been performed, it is really only with the work described at Madison that a further advance seems to have been made.

Bardeen reported a new treatment on the lines of the earlier work but permitting calculations to be made of various properties of the superconductor and their temperature dependence. The treatment is a wave mechanical discussion of the interactions of the electrons both with themselves and with the lattice, and does not appear susceptible to explanation in classical terms. However, one of the most important conclusions is that there must be an energy gap in the distribution of electrons; that is, electrons are not allowed to take up a certain narrow range of energies.

On the experimental side several workers are attacking the problem with fresh techniques and achieving notable results. Tinkham had studied the infrared absorption in superconductors and obtained results that could only be interpreted in terms of an energy gap of similar magnitude to that predicted by Bardeen. Slichter reported on measurements of the relaxation time of nuclear spin resonance, in which a significant difference

was observed between the normal and superconducting states; again in good agreement with Bardeen's theory. Differences between normal and superconducting states had also been detected by Reif, using nuclear resonance techniques, although at present they do not seem susceptible to anything but a qualitative discussion in terms of Bardeen's theory. Morse and Bommel had each made measurements of the attenuation of acoustic waves of megacycle frequencies and again detected differences between the two states, which should give valuable insight into the electron-phonon interactions. Whether Bardeen's theory is adequate to explain all superconductive phenomena remains to be seen, but it is a big step forward.

ONE of the most pleasant items on the conference agenda was the presentation of the first Fritz London Award to Nicholas Kurti of the Clarendon Laboratory, Oxford University, Oxford, England. This Award for outstanding work at low temperatures is generously sponsored by A. D. Little, Inc., and will be offered every two years in memory of Fritz London who was such a well-known figure at previous conferences. One recalls Kurti and Simon's pioneer experiments before the war when they explored a wide range of properties in the region below 1° . After the war, still in association with Simon, Kurti became the active leader of a large group at Oxford which was to succeed first in orienting nuclei, and then in reaching temperatures orders of magnitude lower than any obtained previously.

Until recently most of the experiments on nuclear orientation have been concerned with observing the gamma rays emitted by radioactive nuclei. A random assembly of nuclei emits isotropic gamma radiation, but if the nuclei all point the same way then the radiation pattern will have the characteristic (anisotropic) form of that from a single nucleus. If radioactive nuclei are inserted into appropriate paramagnetic salts, internal forces may be sufficient at low temperatures to orient them and hence produce anisotropy in the gamma radiation. By studying this anisotropy important information may be gained about the decay schemes of the nuclear spin of the nuclei and several papers described experiments of this now well-established type.

At present especial interest in alignment arises from Yang and Lee's suggestion concerning one of the basic wave mechanical postulates of nuclear physics, the conservation of parity. Parity is a purely wave mechanical property which arises when one changes the sign of all the spatial coordinates specifying a wave function $\psi(x, y, z)$. In general, writing $-x$ for x , $-y$ for y , etc., will either leave the wave function unchanged or reverse its sign. The function is said to have even parity if $\psi(x, y, z)$ equals $\psi(-x, -y, -z)$ and odd parity if $\psi(x, y, z)$ equals $-\psi(-x, -y, -z)$. Until recently it had been accepted that no matter what changes may occur in a system, the parity of its wave function remains unchanged.

Difficulties in the interpretation of various nuclear physics experiments led Yang and Lee to point out that

these could be resolved if parity was not always conserved, and they mentioned that a clear test of this hypothesis could be made by observing the β radiation from certain polarized nuclei. As is now well known, the National Bureau of Standards' experiment showed that this suggestion was well founded. Although more typically nuclear experiments have since been performed to demonstrate the nonconservation of parity, it is noteworthy that the first crucial experiment was a low-temperature one.

Roberts, Dabbs, and Walker described experiments in which they observed the anisotropy of the emission of alpha particles and fission fragments from U-233. It is known (from the fact that they have quadrupole moments) that these nuclei are not spherically symmetrical and standard paramagnetic resonance experiments can indicate how the axes of symmetry of the nucleus lie with respect to the magnetic axis. Thus, by aligning nuclei in suitable crystals and observing the anisotropy one may deduce whether the emission of nucleons is more likely to occur from one part of a non-spherical nucleus than another. Such a technique appears to hold great promise for the study of nuclear structure. Another new development was the dynamic production of nuclear polarization at 1°K by Jeffries, who used an elegant method depending on a coupling between the nuclear and electron spins of certain paramagnetic salts.

In a talk following the presentation of the London Award Dr. Kurti described the Oxford experiment on cooling by nuclear demagnetization. In principle, nuclear cooling is similar to the standard method of obtaining low temperatures below 1°K by the adiabatic demagnetization of a paramagnetic salt. In the latter case the salt can be cooled to about that region where it ceases to be paramagnetic, and for ordinary paramagnetic salts the Curie point occurs between 0.01° and 0.001°K. Nuclear moments and the interactions among them are much smaller than those associated with electrons, and thus a material which exhibits nuclear paramagnetism (such as metallic copper) has a Curie point which is very much lower. The main difficulties in using such materials to produce cooling arise because their susceptibilities are so small that it is difficult to magnetize them appreciably. Even using fields as big as 50 kilogauss it was necessary to magnetize the copper specimen at a temperature of about 1/100°K, attained by standard demagnetization techniques. On demagnetization adiabatically from this condition the copper cooled to about 2×10^{-5} °K.

Besides the experiments just mentioned there were many others carried out below 1°K and although the techniques of this temperature region are still quite involved, their use is becoming more widespread. Therefore, the conference was especially interested in two developments which may simplify measurements in this region. The first is the use of a cryostat of He³ rather than He⁴; because He³ has a higher vapor pressure it can be pumped down to as low as 0.3°K. The only difficulty is that He³ is expensive, so one has to work with

a comparatively small quantity in a closed system. The other development is the magnetic refrigerator developed by Daunt, which is now being manufactured by A. D. Little, Inc., and which obtains temperatures below 1° by adiabatic demagnetizations carried out in cyclic processes with the help of superconducting thermal valves. The refrigerator is more complicated than the helium cryostat, but offers in principle the possibilities of reaching considerably lower temperatures. Although only a few experiments have yet been performed in refrigerators, several people are now seriously considering their use and they are slowly becoming part of the low-temperature scene.

BESIDES the work mentioned so far, which falls into fairly well-defined categories, there were also many papers on an assorted range of topics including electric and thermal resistance, specific heats, and magnetism. There is only space to mention a few highlights, chosen perhaps rather arbitrarily. Overton reported accurate calculations of the vibration spectra of atomic lattices using machine computers, an example of the rising part such machines are coming to play in many calculations hitherto too tedious to be adequately treated. Professor Gorter pointed out that besides measuring resonances and susceptibilities, paramagnetism may also be profitably studied by observing spin-lattice relaxation times, and he referred to experiments on these lines being carried out at Leiden. Several speakers discussed the use of persistent currents in superconductors at helium temperatures as memory elements for computers; such elements have a very quick resolving time and may well become of commercial importance. Work described by Bleaney on the determination of atomic structure by paramagnetic resonance was notable for the fact that much of it was done with paramagnetic ions of the man-made transuranic elements. A paper from Harwell described how a liquid hydrogen source was being built into a pile in order to produce an intense source of cold neutrons. In this connection one regretted that no account was given of the work of Blewitt and his colleagues at Oak Ridge who have actually made measurements of thermal properties and internal friction inside a pile at temperatures down to 12°K!

A session was devoted to discussing the absolute temperature scale in the region of 1° to 5°K. As at higher temperatures thermodynamic temperatures in this region are derived from gas thermometry and the results are expressed by quoting the vapor pressure of helium as a function of absolute temperature. In practice, however, the only gas available is helium itself which in this region is far from ideal. It turns out that the best method of setting up an accurate scale is to find one which gives the greatest degree of consistency between the many observations which have been made at these temperatures. In 1955 Clement put forward a temperature scale based, among other things, on the criterion that the resistance of certain electrical (carbon) resistors must vary smoothly with temperature; while van Dijk and Durieux from Leiden based a scale on the

consistency of purely thermodynamic quantities. Both scales represented a substantial improvement on the previous ones, but there were discrepancies between them. However, after further work these discrepancies have been reduced, and Dr. Brickwedde reported that both parties had met at the National Bureau of Standards and decided to work together to produce a final scale which can be put forward for international approval in the coming spring.

Since the Paris Conference in 1955 the low-temperature world has been deprived, through death, of two of its leading members, Professor W. H. Keesom of Leiden and Professor Sir Francis Simon of Oxford, and the conference passed formal resolutions appreciating the work of the two men and expressing its sense of loss. Professor Keesom was of course only known to the older generation of physicists, but Professor Simon was the best-known figure at low-temperature conferences.

More than anyone else, he was responsible for the organization and success of the series of these conferences which have been held since the war. It was therefore very appropriate that a Simon Memorial Lecture was included in the conference; this was delivered by Professor Bridgman, an old friend, whose work had often touched on that of Simon's. He recalled Simon's many achievements in almost all branches of low-temperature physics, from his early days with Nernst to the attainment of a temperature within 20 microdegrees of absolute zero.

Finally, no account of the Madison Conference by one who was there can omit comment on the efficient and happy organization which made the conference both useful and enjoyable. For this we had to thank the sponsors of the conference, the steering committee, and, in particular, Professor J. R. Dillinger together with his colleagues at Madison.

INTRODUCING THE FRITZ LONDON AWARD

Introductory remarks on the occasion of the Fritz London Award ceremony at the 5th international low-temperature conference, Madison, Wisc., August 1957. Dr. Brickwedde is dean of the College of Chemistry and Physics, The Pennsylvania State University.

By F. G. Brickwedde

FRITZ LONDON was greatly admired in the United States and abroad. Though an American by adoption he belonged to the world. Therefore, this Award for low-temperature research bearing his name is international and open to persons of all countries.

The work of Fritz London was reviewed by President W. V. Houston¹ of The Rice Institute in his Fritz London Memorial Lecture at the Conference for Low-Temperature Physics and Chemistry in Baton Rouge, Louisiana, December 1955. His work is not reviewed again here though some of it is recalled to point up Fritz London's approach to research—an ideal approach especially worthy of note.

Fritz London's approach to research was philosophical. He worked in large comprehensive areas of physics. Though he covered extensive areas, he worked with a unit objective or purpose in mind and applied his discoveries, which were theoretical in nature, to problems of apparently diverse nature. Many would aspire to this way of research but few will succeed as London did.

Fritz London earned his Doctor of Philosophy degree in philosophy at the age of 21, but he turned his attention afterwards to physics because he thought the physi-

cal sciences offered a better field for the development of fundamental ideas important in his time. After brilliant work on the homopolar chemical bond, and van der Waals intermolecular forces, he took up the quantum mechanics of aggregates of large numbers of particles, that is, quantum mechanics on a macroscopic scale. He introduced the idea of de Broglie waves of macroscopic dimensions, influenced by the geometry of the specimen, which were superimposed on a substratum of general thermal disorder.

In superconductivity, he saw, in the Meissner effect and the phenomenological equations of H. and F. London, the implication of long-range order of electrons in momentum space, meaning that the electron waves are of large dimensions and the geometry of the specimen is important. In liquid helium, also, the zero momentum of the superfluid implied long de Broglie waves. This relationship of superconductivity and superfluid helium is brought out in London's two-volume monograph, *Superfluids*.

London went on to apply the concept of long de Broglie waves superimposed on a background of thermal motions to explain the interesting diamagnetic proper-