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Resource Letter LH-1 on Liquid Helium

C. T. LANE

Department of Physics, Yale University, New Haven, Connecticut

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This is one of a series of Resource Letters on different topics, intended to guide college physicists to some of the literature and other teaching aids that may help them improve course contents in specified fields of physics. No Resource Letter is meant to be exhaustive and complete; in time there may be more than one letter on some of the main subjects of interest. Comments and suggestions concerning the content and arrangement of letters as well as suggestions for future topics will be welcomed. Please send such communications to Professor Joel Gordon, Chairman, Resource Letter Committee, Department of Physics, Amherst College, Amherst, Massachusetts.

Notation: The letter *E* after the item number means that the reference should be mainly useful for *elementary* courses. In view of the complexity of the subject *elementary* will normally imply junior courses. The letter *I* indicates intermediate (senior and first-year graduates) and *A* indicates advanced (second-year graduates and students beginning research in Physics). An asterisk indicates items particularly recommended for introductory study.

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I. INTRODUCTION

HELIUM gas, which normally consists almost entirely of the isotope ^{4}He, was first liquefied in 1908 by H. K. Onnes, and its thermodynamic properties were roughly determined. The normal boiling point is close to 4.18°K, this being the lowest figure for any cryogenic fluid, except the isotope ^{3}He. At first liquid helium was employed mainly as a tool; its low temperature permitted the discovery, also by Onnes, of the important phenomenon of superconductivity. As a matter of fact, it required nearly 30 years of experimentation before it became clear to physicists that liquid helium itself was, under certain circumstances, an exceedingly unusual liquid; unique, in fact, in our experience.

As a result of many contributions over the past 50 years, the following points seem reasonably established. Liquid helium persists as a liquid, without freezing into the solid, down to absolute zero, provided that it is cooled under its own vapor pressure. Only by pressurizing the liquid can it be converted to the solid; this requires approximately 26 atm near 0°K. If the temperature of the fluid is reduced (by pumping off the vapor) below about 2.2°K (called the "λ point"), a remarkable change in its properties commences. For convenience, we call the liquid "helium I" (hereafter, He I) when above 2.2°K and "helium II" (hereafter, He II) when below. He I is unexceptional in its properties; it can be said to be, and essentially is, a "classical" fluid.

But He II exhibits quantum effects on a macroscopic scale and is often called a *quantum liquid* or a *superfluid*.

These large-scale quantum effects exhibit themselves in many ways. For instance, there are several acceptable methods, all giving concordant results, for measuring the viscosity coefficient of any ordinary liquid. But, with He II, these same methods produce widely divergent results. By Poiseuille flow, the result is less than 10^{-11} P (the viscosity of water at room temperature is 10^{-2} P); by the rotating-cylinder or the oscillating-disk method the result is about 10^{-5} P. With convection currents suppressed, ordinary liquids, including He I, have a notoriously small thermal conductivity. But Keesom, in 1936, found that He II could have a thermal conductivity which was some 800 times that of metallic copper. Again, Allen and Jones, in 1938, found that, provided the He II was confined in a narrow channel, a small temperature gradient could produce an ordered motion of the liquid with velocities of the order of several meters per second ("fountain effect"). Kapitza, in 1941, showed that He II, when flowing through narrow channels (the order of 1 μ), possessed zero entropy; on the other hand, when it was unconfined, it possessed a finite entropy. Finally, Pickard and Simon showed that He II, again unconfined, had a specific heat which was proportional to the cube of the temperature when the latter was sufficiently low. In other words, this highly-mobile fluid at lowest temperatures behaves, thermodynamically, as does a Debye solid.

Naturally, these bizarre experimental results soon attracted the attention of a number of theorists, among them F. London, L. Tisza, and L. D. Landau. The gist of these theories is that we may think of He II as composed of two noninteracting and interpenetrating fluids—i.e., the "normal" component, essentially classical in its properties, possessing both viscosity and entropy, plus the "superfluid" component, possessing neither entropy nor viscosity. For convenience, we may think of the total density ρ of the He II as divided into two parts such that $\rho=\rho_n+\rho_s$, where the subscripts refer to the normal and superfluid components, respectively. The ratio ρ_s/ρ is temperature-dependent, being zero at the λ point and unity at absolute zero. This in turn implies two velocity fields—one for each component—and leads to two hydrodynamic (Navier–Stokes) equations of motion as compared to only one for an ordinary fluid. Clearly, the entropy of He II arises solely from the normal component. These hypotheses yield a qualitative explanation of most of the above results; for example, the peculiar properties of He II when it is confined to narrow regions. In such places, the normal component is "filtered out" (owing to its finite viscosity) and only the superfluid can flow.

Actually, of course, the above "two-fluid" model is too classical in concept. We believe that He II, as a thermodynamic system, possesses a macroscopically occupied quantum-mechanical ground state (the superfluid); the excited states of the system being what we call the normal component. The excited states contain two types of quasiparticles, namely phonons (Debye sound waves) and rotons, the latter being of the nature of elementary vortex rings. An energy gap separates the roton ground state from the superfluid, and it can be shown that without this, frictionless flow could not occur. Nevertheless, the simple hydrodynamical two-fluid model has been extremely useful in predicting new phenomena in He II. Among these is the "second sound," predicted by Landau and also by Tisza, and demonstrated experimentally by Peshkov and others. This consists of temperature pulses which propagate as a virtually undamped and dispersionless wave motion. Above 1°K, the maximum velocity of this wave motion is around one-tenth that of ordinary sound and, unlike the latter, it vanishes at the λ point.

On the other hand, the deeper insight which quantum mechanics provides has also had its successes—the chief of which is the prediction, by L. Onsager and independently by R. P. Feynman, that the hydrodynamic circulation of the superfluid component should be quantized in units of $h/m \approx 10^{-3}$ cm^2/sec (h is Planck's constant and m the mass of the helium atom), an effect which has also been experimentally verified.

II. SELECTED REFERENCES—SUPERFLUID HELIUM

1.I **"Two Different Liquid States of Helium."** W. H. KEESOM AND M. WOLFKE. Leiden Commun. No. 190b (1927). The first statement of the idea that some sort of phase transformation occurs in liquid helium and the introduction of the terminology "He I" and "He II." We know now that the phase transition is "second order," i.e., with a specific heat jump but zero latent heat.

2.I **"Ueber die spezifische Waerme des fluessigen Heliums."** W. H. KEESOM AND K. CLUSIUS. Leiden Commun. No. 219e (1932). Discovery of an anomaly in the specific heat of liquid helium at a temperature near 2.2°K. The shape of the specific-heat-versus-temperature curve, in this region, roughly resembles the Greek letter lambda—hence the name applied to the temperature where the peak occurs.

Modern measurements, by W. M. Fairbank and collaborators, have been made to within a microdegree either side of the transition, which they place at 2.172°±0.002°K. On either side of the λ point, the specific heat at saturated vapor pressure (C) is found to be given by

$$C=4.55-3.00\log_{10}|T-T_\lambda|-5.20\Delta \qquad \text{J/g/deg},$$

where $\Delta=0$ for $T<T_\lambda$ and $\Delta=1$ for $T>T_\lambda$. It thus appears that the specific heat assumes an infinite value at the transition; although, of course, no actual measurement could ever prove an infinite value (Ref. 37, Vol. 3).

3.E **"The Scattering of Light by Liquid Helium."** J. C. MCLENNAN, H. D. SMITH, AND J. O. WILHELM. Phil. Mag. **14**, 161 (1932). The first visual evidence for a λ transition. Upon decreasing the temperature of the liquid through the λ point, all ebullition suddenly ceased. We know today that this indicates a much larger effective thermal conductivity in He II than that in He I.

4.I **"On the Heat Conductivity of Liquid Helium."** W. H. KEESOM AND A. P. KEESOM. Physica **3**, 359 (1936). First quantitative experiment showing that He II had an enormous effective thermal conductance. The heat flow is not proportional to the temperature gradient, as it should be classically. On the two-fluid model, this arises because the superfluid component carries no entropy. If we attempt to impress a temperature gradient, the superfluid is converted to normal at the hot end, thus disturbing the equilibrium imposed by the ambient temperature. Hence, superfluid flows from the cold end, giving rise to a return flow of normal fluid to preserve mass balance. The superfluid carries no entropy but the normal does, hence heat in large amounts is transferred from the hot to the cold end. This process, very different from classical heat conduction, was termed "internal convection" by F. London, although it clearly has nothing to do with gravity.

5.I **"New Phenomena Connected with the Heat Flow in Helium II."** J. F. ALLEN AND H. JONES. Nature **141**, 243 (1938). Discovery of the "fountain effect." Another example of internal convection, the normal-component flow being suppressed in the narrow channel owing to its finite viscosity.

6.I **"Viscosity of Liquid Helium below the λ-Point."** P. L. KAPITZA. Nature 141, 74 (1938). First measurement showing that the viscosity of He II, as measured by the Poiseuille flow method, was less than 10^{-9} cgs units. This led to the introduction of the term *superfluid.*

7.A **"The λ-Phenomenon of Liquid Helium and the Bose–Einstein Degeneracy."** F. LONDON. Nature **141**, 643 (1938). The first attempt to account for the properties of He II theoretically. An ideal gas, obeying Bose–Einstein statistics, exhibits a peculiar "condensation" effect below a certain critical temperature which is computed as 3.13°K for particles with the mass of the ^{4}He atom. The particles increasingly enter a zero-entropy ground state which contains all the atoms at 0°K. Hence, the entropy of the gas below the transition temperature is entirely due to the uncondensed atoms. London pointed out that this behavior seemed closely analogous to that of the nonideal fluid He II.

8.I **"Transport Phenomena in Helium II."** L. TISZA. Nature **141**, 913 (1938). The first suggestion for a two-fluid model for He II, based on London's proposal of Bose–Einstein condensation. In particular, the concept of internal convection is clearly set forth. Somewhat later (1940), Tisza, on the basis of this model, was able to show that small entropy fluctuations in He II should propagate as an undamped and dispersionless wave motion.

9.I **"Surface Transport in Liquid Helium II."** J. G. DAUNT AND K. MENDELSSOHN. Nature **143**, 719 (1939). When He II flows out of an insulated vessel through a narrow channel, the liquid in the vessel heats up, and vice versa. This inverse of the fountain effect reflects the fact that the superfluid carries zero entropy, and it was called by the discoverers, "the mechano-caloric effect."

10.A **"The Theory of Superfluidity of Helium II."** L. D. LANDAU. J. Phys. (USSR) **5**, 71 (1941). A classic paper in low-temperature physics which firmly introduced the two-fluid model and which, in many ways, was well in advance of its time.

It is a rather curious mixture of classical concepts backed up with a deep quantum-mechanical intuition. For example, Landau placed a restriction on the superfluid component flow velocity ($\mathbf{v}_s$) whereby curl $\mathbf{v}_s=0$. The evidence that this criterion is true is substantial, albeit indirect; in any event it has been an important guideline in the further development of the theory of superfluids.

Again, the paramount question as to why the superfluid flows without friction (unanswered in London's approach) emerges from the nature of the spectrum of the excited states. Imagine the fluid, at 0°K, flowing through a horizontal pipe. If there is to be friction, the stream must slow down yielding up kinetic energy, i.e., creating a phonon or a roton. But the energy of these particles is finite; hence there must exist some "critical" velocity of flow below which the stream flows frictionlessly.

In addition to accounting for practically all the prior experimental effects, this theory suggested new and important experiments which were later carried out successfully. The Nobel Prize was awarded to Landau partly on the basis of this work.

11.I **"Heat Transfer and Superfluidity of Helium II."** P. L. KAPITZA. J. Phys. (USSR) **5**, 59 (1941). An elegant piece of experimentation showing, among other things, that the entropy of the superfluid component of He II is zero—as required by Landau's theory and London's.

12.I **"A Direct Observation of Two Kinds of Motion in Helium II."** E. ANDRONIKASHVILI. J. Phys. (USSR) **10**, 201 (1946). Another beautiful experiment, based on Landau's theory, in which the fraction of the He II atoms which are in excited states (normal component) is measured as a function of the temperature. The period of a torsion pendulum, consisting of a stack of closely spaced mica disks immersed in He II, is measured as a function of temperature. The curl-free superfluid ignores the motion; but the normal component, trapped between the disks, moves with them and adds to the system's moment of inertia.

13.I **"Determination of the Velocity of Propagation of the Second Sound in Helium II."** V. PESHKOV. J. Phys. (USSR) **10**, 389 (1946). The earliest confirmation of yet another prediction of the Landau theory, namely that temperature pulses in He II will propagate as an undamped, dispersionless wave. According to Landau, if T^* is a small (order-of-millidegrees) temperature excursion from the ambient temperature (T_0), then

$$\frac{\partial^2 T^*}{\partial t^2}=\left[\frac{\rho_s}{\rho_n}\cdot\frac{T_0 S_0^2}{C_0}\right]\frac{\partial^2 T^*}{\partial x^2}.$$

Here S_0 is the entropy of the liquid and C_0 its specific heat, both at T_0. This is the equation of an undamped, dispersionless wave and is quite different from classical heat conduction. For, in the latter case, the differential equation is first order in the time dependence, leading to a wave which suffers both dispersion and attenuation. Peshkov generated standing waves in a liquid column by means of an ac-fed heater and detected them, at resonance, with a resistance thermometer. Hence, the method is analogous to that used in an undergraduate Physics laboratory to measure the velocity of sound in air with a resonating column. His results, and those of others, are accurately in accord with the above formula.

14.I **"Second Sound in Liquid Helium II."** C. T. LANE, HENRY A. FAIRBANK, AND WILLIAM M. FAIRBANK. Phys. Rev. **71**, 600 (1947). An interesting variation on Peshkov's method, originally suggested by Onsager, for the determination of second-sound velocities. The second sound in the fluid converts itself into first sound at a liquid–vapor interface and is detected by a microphone in the helium vapor. In recent years the experiment has been used as a student laboratory exercise.

15.A **"Second Sound Propagation below 1°K."** D. DE KLERK, R. P. HUDSON, AND J. R. PELLAM. Phys. Rev. **93**, 28 (1954). The previously cited measurements of the second-sound velocity extended down only to about 1°K, where the velocity is of the order of 19 m/sec. In this work the temperature ranges from 1.1° to 0.015°K. The velocity is found to rise steadily to 137 m/sec ($u_1/\sqrt{3}$, where u_1 is the first-sound velocity) at 0.5°K and thence extrapolates to 239 m/sec (u_1) at absolute zero.

This is a case where Landau's formula (our Ref. 13) fails. Clearly, it becomes indeterminate as $T\rightarrow 0$°K but, remembering that near absolute zero the excitations are exclusively phonons, Landau shows that the second-sound velocity should approach $u_1/\sqrt{3}$ as $T\rightarrow 0$°K, which the experiment shows to be false. The difficulty lies in the fact that he uses a continuum theory whereas, in fact, the phonon mean-free path becomes very long—greater than the dimensions of the apparatus—at the lowest temperatures. This results in phonons' traveling directly from transmitter to receiver, their speed being appropriately that of first sound.

16.I **"The Rotation of Liquid Helium II."** D. V. OSBORNE. Proc. Phys. Soc. (London) **63**, 909 (1950). The first of many "rotation" experiments with He II. The liquid was rotated (angular velocity ω) in a cylindrical vessel and the shape of the free surface measured. The result showed this to be parabolic, meaning that the superfluid was rotating in solid-body motion. For such a motion, the curl of the fluid velocity is 2ω. But, according to the Landau theory, the curl of the superfluid component's velocity should vanish. This discrepancy was later removed by the discovery that the circulation of the superfluid is quantized.

17.I **"Application of Quantum Mechanics to Liquid Helium."** R. P. FEYNMAN. Progr. Low Temp. Phys. **1**, 17 (1955). Another classic paper in which Landau's theory is refined and put on a firmer quantum-mechanical basis. In London's original theory of superfluid helium (Ref. 7), the fact that the ^{4}He atom is a boson was, of course, crucial; but this feature is quite absent in Landau's approach. Feynman's extension of the Landau theory, however, presents strong arguments tending to show that only an aggregate of bosons can exhibit superfluidity. In addition, Feynman (i) deduces, from first principles, the "Landau spectrum," the quasiparticle energy-versus-momentum curve which represents the normal component; and (ii) shows that the hydrodynamic circulation of the superfluid component should be quantized, a result also found previously by Onsager.

18.A **"Theory of Inelastic Scattering of Cold Neutrons from Liquid Helium."** M. COHEN AND R. P. FEYNMAN. Phys. Rev. **107**, 13 (1957). Extending the ideas proposed in Ref. 17, the authors suggest a method whereby the Landau spectrum could be directly measured by scattering "cold" neutrons with He II.

19.A **"Excitation of Rotons in Helium II by Cold Neutrons."** H. PALEVSKY, K. OTNES, AND K. E. LARRSON. Phys. Rev. **112**, 11 (1958). Following the suggestions in Ref. 18, the roton branch of the Landau spectrum is empirically determined for the first time. Neutrons, made suitably monochromatic by passage through a filter (wavelength$\sim$4 a.u.), are allowed to impinge on He II at a given temperature, and their wavelengths (i.e., momenta), before and after scattering, are determined with a crystal spectrometer. The incident neutron generates a roton (or phonon) and, by applying conservation of energy and momentum, the energy and momentum of the quasiparticle are measured. This work has been greatly extended by similar experiments at Los Alamos and Chalk River in recent years.

20.A **"Third and Fourth Sound in Liquid Helium II."** K. R. ATKINS. Phys. Rev. **113**, 962 (1959). It is pointed out that, in addition to first and second sound, two additional types of wave propagation are possible in superfluid helium. "Third sound" is a surface wave of long wavelength, which occurs in a liquid film attached to a solid wall. The normal component remains stationary, and the superfluid component oscillates parallel to the wall. "Fourth sound" may exist in two-sided narrow channels. The wave propagation is the same as that for third sound—with, however, this important difference. In the latter case, temperature variations produce evaporation from the free surface of the film; but in the former case, the liquid, constrained by the channel, does not evaporate. Hence, density, as well as temperature, fluctuations may occur.

Both types of theoretically predicted wave propagation have been found experimentally: third sound by C. Everitt, K. Atkins, and A. Denenstein [Phys. Rev. Letters **8**, 161 (1962)] and fourth sound by I. Rudnick and K. Shapiro [Phys. Rev. Letters **9**, 191 (1962)].

21.I **"The Detection of Single Quanta of Circulation in Liquid Helium II."** W. F. VINEN. Proc. Roy. Soc. (London) **A260**, 218 (1961). The first, and most ingenious, experiment to detect the quantum of circulation in superfluid helium. The frequency of free oscillation in a thin wire immersed in He II is measured electrically. If a circulation around the wire is present, this frequency is modified owing to extra forces arising from Bernoulli's principle. In addition to confirming the existence of the quantum, the experiment is also noteworthy for demonstrating the existence of persistent (i.e., very-long-lifetime) hydrodynamic currents in the superfluid. The experiment has recently been repeated, with improved techniques, by S. C. Whitmore and W. Zimmermann [Phys. Rev. Letters **15**, 389 (1965)], who were able to observe one, two, and three quantum units.

22.A **"Quantized Vortex Rings in Superfluid Helium."** G. RAYFIELD AND F. REIF. Phys. Rev. **136**, A1194 (1964). Ions, positive and negative, moving through He II at low temperature (0.3°K) are shown to attach themselves to elemental "smoke-ring"-type vortices which possess one quantum of circulation. A curious result follows: that the apparent kinetic energy of the moving ion decreases with increasing velocity, in accordance with the laws of classical hydrodynamics. The experiment also yields a value for the radius of the "hollow" core of the vortex, which turns out to be about 1.3 a.u.

23.A **"Persistent Currents in Superfluid Helium."** J. REPPY AND D. DEPATIE. Phys. Rev. Letters **12**, 187 (1964). The experiment measures the angular momentum of the persistent He II hydrodynamic currents, which are generated by first rotating the container and then bringing it to rest. The currents are then detected by radiant heating of the fluid, which converts the superfluid to normal, and observing the angular velocity which the container acquires. The currents were observed to have undiminished intensity for as long as 12 h, after which the experimenter's patience gave out. If the current is generated near the λ point, and if then, without further rotation, the fluid is cooled to a much lower temperature, the angular momentum is found to increase in the same way as ρ_s increases. This is consistent with the zero curl condition and appears to mean, microscopically, that the superfluid occupies a single quantum state.

24.A **"Second Sound in Solid Helium."** C. C. ACKERMAN, B. BERTMAN, H. A. FAIRBANK, AND R. A. GUYER. Phys. Rev. Letters **16**, 789 (1966). Dielectric solids have a finite thermal conductivity for which phonons are responsible. At sufficiently low temperatures, in a crystal without appreciable chemical and isotopic impurities, the "phonon gas" may transmit a heat current without resistance. This is quite different from the situation in an ordinary gas, and it arises from the fact that phonons, unlike atoms, can be created and annihilated. The experiment presents evidence tending to show that temperature pulses in a single crystal of ^{4}He, a nearly ideal solid from the point of view of purity, are transmitted with negligible attenuation. In this respect the process is similar to second-sound propagation in He II.

III. BOOKS

There are comparatively few books devoted exclusively, or nearly so, to the subject of superfluid helium. There exist a number of others on the general topic of low-temperature Physics, which contain odd chapters devoted to this subject. Some of the latter are included in the following listing.

25.I **Helium.** W. H. KEESOM. (Elsevier Publ. Co., Inc., New York, 1942). An encyclopedic account of the properties of ^{4}He in the gas, liquid, and solid phases. Describes many of the pioneer experiments performed at Onnes's laboratory in Leiden from 1908 up until about 1940 and, in this respect, is a valuable source-reference work.

26.I **Supplement to Helium.** E. ANDRONIKASHVILI AND E. LIFSHITZ. (Moscow, 1949). (English translation by Consultant's Bureau, Inc., New York, 1959.) A short volume aimed, at the time of writing, in bringing Keesom's book up to date. It constitutes a useful supplement to the earlier work.

27.A **Superfluids, Volume II.** F. LONDON. (John Wiley & Sons, Inc., New York, 1954.) An elegant and purely theoretical treatment of superfluid helium by one of the pioneer workers in the field. It emphasizes London's own contributions, but Landau's are by no means neglected. A "must" for anyone interested in the theory of liquid helium.

28.A **Liquid Helium.** K. R. ATKINS. (Cambridge University Press, Cambridge, England, 1959.) One of the most definitive accounts of superfluidity in both its experimental and theoretical aspects. Recommended for reference purposes and graduate-level study.

29.I **Superfluid Physics.** C. T. LANE. (McGraw–Hill Book Co., New York, 1962.) The majority of the text is on superfluid helium. It is written at intermediate level and intended as an introduction to the subject. Suitable for undergraduates with some background in Physics.

30.A **Introduction to the Theory of Superfluidity.** I. M. KHALATNIKOV. (W. A. Benjamin, Inc., New York, 1965.) An up-to-date account of the general theory of superfluid helium by one of the leading Soviet theoreticians in the field, in which He II is treated from both the microscopic and the hydrodynamic point of view. Of particular interest is the chapter on the weakly interacting nonideal Bose gas, wherein it is shown that a condensed state of zero momentum exists coupled with low-lying excited states which are phonons. Many other topics are discussed, including interactions between excitations, second sound, and helium in rotation. Recommended especially for the research worker and advanced graduate students. Landau's paper (our Ref. 10) is reproduced in full in an Appendix.

31.E **Cryophysics.** K. MENDELSSOHN. (Interscience Publishers, Inc., New York, 1960.) One chapter out of eight is devoted to liquid helium, but this contains a surprising amount of information. The writing is both elementary and authoritative.

32.I **Heat and Thermodynamics.** MARK W. ZEMANSKY. (McGraw–Hill Book Co., Inc., New York, 1957.) This well-known undergraduate text contains a chapter on low-temperature physics which is especially recommended for students seeking an introduction to the subject.

***33.E** **Near Zero.** D. K. C. MACDONALD. (Anchor Books, Doubleday and Co., New York, 1961). A paperback, entertainingly written, but not exclusively on liquid helium.

IV. REVIEW ARTICLES

34.A **"The Problem of Liquid Helium."** J. G. DAUNT AND R. S. SMITH. Rev. Mod. Phys. **26**, 172 (1954). A very readable account of many of the principal experimental advances occurring between 1939 and 1953.

35.I **"Liquid Helium."** K. MENDELSSOHN. In *Handbuch der Physik*, S. Flügge, Ed. (Springer-Verlag, Berlin, 1956), Vol. 15, p. 370. A well-written summary of the work on liquid helium up to 1956.

36.A **"The Rotation of Liquid Helium II."** H. E. HALL. Advan. Phys. **9**, 89 (1960). A comprehensive review, including considerable theoretical treatment, of the general problem of superfluid helium in rotation.

37.A **"Progress in Low Temperature Physics."** C. J. GORTER, Ed. (Interscience Publishers, Inc., New York.) In four volumes: Vol. 1 (1955), Vol. 2 (1957), Vol. 3 (1961), and Vol. 4 (1964). Each volume consists of many chapters, each by separate authors, dealing with many different aspects of low-temperature Physics, including a number on liquid helium. The whole set constitutes a useful reference work.

38.A **"Liquid Helium—Course 21."** G. CARIERI, Ed. Proc. Intern. School Phys. "Enrico Fermi" **16**, 000 (1963). A symposium, by many specialists, dealing exclusively with liquid helium, including ^{3}He, and covering a wide range of topics of contemporary interest. Especially recommended for the summaries of the current theoretical situations for the two heliums.

39.A **"Low Temperature Physics LT9."** J. G. DAUNT, D. O. EDWARDS, F. J. MILFORD, AND M. YAQUB, Eds. Proc. Intern. Conf. Low Temp. Phys. 9th, Columbus, Ohio, 1964, 2 vols. (1965). The proceedings of the latest conference on low-temperature Physics held in September 1964. In addition to Review Articles, many research reports of work in progress by various contributors are included. Volume 1 (Part A) is largely concerned with various aspects of liquid helium.

*40.E **"Superfluidity."** E. Lifshitz. Sci. Am. **198**, 30 (June 1958). A popular account by one of the leading Soviet experts in the field. Contains a photograph of "Kapitza's spider," illustrating the peculiarities of heat-induced motion in He II.

*41.E **"Superfluidity and Quasi-Particles."** F. Reif. Sci. Am. **203**, 139 (November 1960). A nonmathematical account of the two-fluid model of He II with a simplified presentation of many of the classic experiments. Includes a good photograph of the fountain effect.

*42.E **"Quantized Vortex Rings in Superfluid Helium."** F. Reif. Sci. Am. **211**, 116 (December 1964). A popular presentation of the experiments in which smoke-ring-type vortices are produced by the motion of ions in superfluid helium.

V. LIQUID ^{3}He

It was believed, for a long time, that liquid ^{3}He ought not to be a superfluid. This belief arose because of the crucial role which the Bose–Einstein statistics play in both London's theory as well as in Feynman's extension of that of Landau. In both approaches only bosons can exhibit superfluidity, and ^{3}He is a fermion. This theoretical view seemed to be confirmed by the fact that no superfluid transition in pure ^{3}He could be found experimentally in the temperature range from 3.2°K (the normal boiling point) to about 0.1°K. Set against this reasoning was the fact that electrons, also fermions, become superfluid in superconductors.

The resolution of this dilemma came with the advent of the BCS theory of superconductivity: two electrons become "paired," creating what might be called a "pseudoboson." Following the great success of the BCS theory, the suggestion was made that a similar process might occur with ^{3}He at some sufficiently low temperature. If so, then ^{3}He might show something like a λ transition. The problem, however, has proved more intractable than BCS, and no reliable estimate for the transition temperature has proved possible—except that it would probably be very low. The question must, therefore, be settled by appropriate experimentation; but the experiments are something like an order of magnitude more difficult than most encountered with ^{4}He. And, to date, the experimental evidence is completely contradictory.

The situation with respect to solutions of ^{3}He in ^{4}He is relatively clearer. These form superfluids whose λ temperatures decrease with increasing ^{3}He concentration. For instance, a 28.2% mixture of ^{3}He in ^{4}He has a λ transition at 1.56°K. However, below approximately 0.8°K, a curious phenomenon occurs. The solution splits spatially into two layers, one being much richer in ^{3}He than the original mixture and the other correspondingly less rich. For example, in an original 20% ^{3}He mixture, one layer will contain about 90% ^{3}He and the other around 10% when cooled to 0.3°K.

43.I **"Phase Separation in He^3–He^4 Solutions."** G. K. Walter and W. M. Fairbank. Phys. Rev. **103**, 262 (1956). The discovery of spatial phase separation in ^{3}He–^{4}He solutions.

44.A **"Possible Phase Transition in Liquid ^{3}He."** V. J. Emery and A. M. Sessler. Phys. Rev. **119**, 43 (1960). By using the BCS methodology, it is predicted that ^{3}He should exhibit superfluidity with a transition temperature between approximately 0.05° and 0.1°K.

45.I **"Superfluidity of ^{3}He."** V. P. Peshkov. Soviet Phys.—JETP **19**, 1023 (1964). A measurement of the specific heat of ^{3}He as a function of the temperature down to a few millidegrees above absolute zero. A small, but sharp, peak in the curve was observed at 0.0055°K, which the author, arguing by analogy with the specific-heat anomaly in ^{4}He, identifies as a λ point.

46.A **"Absence of Superfluidity in Low Pressure Liquid ^{3}He above 0.0035°K."** W. R. Abel, A. C. Anderson, W. C. Black, and J. C. Wheatley. Phys. Rev. Letters **14**, 129 (1965). In a specific-heat measurement similar to that in Ref. 45, no such peak as that reported by Peshkov was observed down to about 0.004°K. Additional measurements on the nuclear susceptibility and the self-diffusion coefficient for the magnetization, using spin–echo techniques, fail to produce evidence of superfluidity down to 0.0035°K.

47.A **"Liquid and Solid ^{3}He."** N. Bernardes and D. F. Brewer. Rev. Mod. Phys. **34**, 190 (1962). A review article dealing with theoretical and experimental work on ^{3}He prior to 1962.

Apart from the question of possible superfluidity in liquid ^{3}He, there is considerable interest attached to its properties as an interacting Fermi fluid with uncharged particles. This arises because it is the single known example of this type of liquid. The main theoretical impetus is again due to Landau, who treats ^{3}He as a nonideal gas of quasiparticles equal in number to the number of ^3He atoms. This gas obeys Fermi–Dirac statistics and has a temperature-dependent energy-versus-momentum spectrum. It turns out that, at very low temperatures, the specific heat and entropy of ^3He should be the same as those of an ideal Fermi gas of the same atomic volume but with an effective mass greater than the true mass of the atom. This seems to be generally in accord with experiment.

Another property of interest arises from the fact that, since the ^3He atom is a fermion, the liquid should show a (nuclear) paramagnetism, as should the solid. A good deal of experimentation by various workers has shown that, in general, the susceptibility tends to become independent of temperature (compare the ideal Fermi gas) at temperatures below about 0.1°K; whereas at higher temperatures (about 0.5°K), it obeys Curie's law.

Additionally, a unique form of wave propagation, called, by Landau, "zero sound," has been theoretically predicted for liquid ^3He. This effect, which occurs only at very low temperatures, consists of a distortion of the Fermi surface. Ordinary sound waves correspond to an oscillatory displacement of the Fermi surface as a whole without a change in its shape. In zero sound the surface suffers elliptical elongation in the direction of motion, oscillating back and forth. The effect has recently been confirmed experimentally.

48.I **"Fermi–Dirac Degeneracy in Liquid ^3He below 1°K."** WILLIAM M. FAIRBANK, W. B. ARD, AND G. K. WALTERS. Phys. Rev. **95**, 566 (1954). The first measurement of the nuclear magnetic susceptibility of liquid ^3He. The temperature range covered was from 0.23° to about 2.1°K, and used nuclear magnetic resonance techniques. At the lower temperatures the susceptibility tended to become temperature-independent, whereas at the highest it approached a Curie law behavior. The results were well represented by supposing that the liquid behaved as an ideal Fermi gas with a degeneracy temperature of 0.45°K. An ideal Fermi gas with the same density and atomic mass as liquid ^3He would have a degeneracy temperature of 5°K.

49.A **"The Theory of a Fermi Liquid."** L. D. LANDAU. Soviet Phys.—JETP **3**, 920 (1957). The pioneer work on the theory of the Fermi liquid. The experimental result that the susceptibility becomes independent of temperature at the lowest temperatures is explained and, as in the case of the ideal gas, is due to the action of the exclusion principle. The low value of the degeneracy temperature is accounted for by ferromagnetic-type exchange interaction.

50.A **"Oscillations in a Fermi Liquid."** L. D. LANDAU. Soviet Phys.—JETP **5**, 101 (1957). The theoretical prediction of zero sound.

51.A **"Propagation of Zero Sound in Liquid ^3He at Low Temperatures."** W. R. ABEL, A. C. ANDERSON, AND J. C. WHEATLEY. Phys. Rev. Letters **17**, 74 (1966). Strong experimental evidence is presented for the existence of zero sound commencing at a temperature of about 10 mdeg Kelvin, the velocity being approximately 194 m/sec. In the Landau theory the mean free path of a quasiparticle tends to infinity in the vicinity of the absolute zero and, since a compressional wave cannot be propagated in a gas when the wavelength is small as compared to the mean free path, no first sound can occur at the lowest temperatures. The experiment bears this out, the first sound (velocity about 188 m/sec) being rapidly attenuated in the region just above 10 mdeg.

52.A **"Cryogenics, Helium Three."** J. G. DAUNT AND D. O. EDWARDS. Ann. Rev. Phys. Chem. **15**, 83 (1964). An excellent review article dealing with various phenomena in both liquid and solid ^3He. Among a wide range of topics discussed are the specific heat, paramagnetism in both liquid and solid, and the pressure–temperature phase diagram.

VI. PRACTICAL APPLICATIONS

The saturated vapor pressure of ^4He at 1°K is approximately $\frac{1}{10}$ mm Hg and, by extrapolation, would be about 10^{-3} at around 0.65°K. Thus, the usual method of creating low temperatures by pumping on the vapor is clearly impracticable below about 0.8°K. In order to achieve lower temperatures, three techniques are currently being employed, each depending on liquid ^4He as a precoolant.

The oldest of these, and the one whereby the lowest temperatures are achieved, is that of adiabatic demagnetization (sometimes called magnetic cooling). This depends on the fact that certain paramagnetic salts (e.g., iron ammonium alum) show a sharp decrease in entropy when placed in a magnetic field at helium temperatures. If the field is removed adiabatically, starting at a temperature of about 1°K, the solid will cool to a much lower temperature and may be used as a heat sink. The method suffers from the disadvantage that the temperature is time-dependent as the salt slowly heats up due to unavoidable thermal leaks. A good account of the thermodynamics of the process will be found in our Ref. 32.

The second method employs a bath of liquid ^{3}He condensed by means of liquid ^{4}He. This technique makes use of the fact that the vapor pressure of liquid ^{3}He at a given temperature is much higher than that of liquid ^{4}He. Thus vapor pumping, with this fluid, is able to achieve temperatures as low as 0.2°K in a liquid bath. Since the fluid has a latent heat, such temperatures can be maintained independent of time, which is a great asset in many experiments.

The third technique, going by the name of the helium-dilution refrigerator, makes use of dilute mixtures of ^{3}He in ^{4}He. Helium-4, below 1°K, possesses an almost negligible entropy, so that a dilute solution of ^{3}He atoms behaves as would a gas. Hence, further dilution produces a cooling analogous to the adiabatic expansion of an ordinary gas. Temperatures as low as 0.07°K have been reported with this method, which again gives a time-invariant bath temperature.

53.I **"^{3}He Cryostat for Operation to 0.2°K."** D. Walton. Rev. Sci. Instr. **37**, 734 (1966). A superior ^{3}He refrigerator producing a steady temperature of 0.21°K with a heat input of 4.7 μW.

54.A **"A Helium-3 Dilution Refrigerator."** H. E. Hall, P. J. Ford, and K. Thomson. Cryogenics **6**, 80 (1966). The latest of several versions, by various authors, of this device. The idea originated with H. London in 1951 and is made practical by the discovery of the phase-separation process (our Ref. 43). The lowest temperature reported is 0.07°K and is time-independent. A commercial version is being manufactured by the Oxford Instrument Co., Oxford, England.

Liquid helium is currently available, in the United States, from a variety of commercial sources (e.g., Air Reduction Co., Gardner Cryogenics, etc.). The price is rather high, several dollars per liter, if purchased in medium quantities. Pure gaseous ^{3}He is available from the U. S. Atomic Energy Commission. The cost of the raw material sufficient to produce about 1 cc of liquid is around $60.

55.I **Experimental Techniques in Low-Temperature Physics.** G. K. White. (The Clarendon Press, Oxford, England, 1959). A useful book describing the various technical methods employed in low-temperature research.

VII. FILM

56. **"Liquid Helium II, The Superfluid."** 39 min, b&w Instructional Media Center, Michigan State University, Ann Arbor, Michigan 48823. A 16 mm, sound film, available for rental or purchase.