Liquid Helium-3: A New Superfluid Suggested

For more than 30 years scientists have known that liquid helium-4 has some very strange properties at temperatures near absolute zero. At 2.2°K liquid helium-4 starts to lose viscosity and resistance to heat flow, and part of the liquid becomes a superfluid. Heat flows so rapidly through superfluid helium that it boils without bubbling, and the superfluid will flow easily through glass capillaries made so fine that ordinary gases and liquids cannot penetrate them. Until last year it appeared that helium-4 was a special case. No other liquids had been found to become superfluid, not even helium-3, which is the rare isotope of natural helium (about 1 part in 10^7). But last year physicists at Cornell University, Ithaca, New York, reported some unexpected changes of phase in helium-3 at extremely low temperatures. Since then scores of experimentalists and theoreticians have been examining liquid helium-3. A new paper by researchers in Helsinki, Finland, reports evidence that helium may have a superfluid component. In fact, liquid helium-3 appears to have at least two superfluid phases, but none of the phases of helium-3 are well understood.

Helium-4 becomes superfluid because it obeys Bose-Einstein quantum statistics, which are associated with particles with integral spin. [The helium-4 nucleus has integral spin (zero) because it has an even number of nucleons; the helium-3 nucleus has spin ½.] Helium-3 obeys Fermi-Dirac statistics. The distribution of energies for a fluid of Fermi-Dirac particles does not permit all the particles to settle into one low-energy state, but the distribution for Bose-Einstein particles does. Thus, superfluidity in helium-4 occurs when all the particles of the fluid "condense" into a state of low momentum. However, a state with integral spin could be achieved in helium-3 if atoms were paired. Soon after the development of the Bardeen-Cooper-Schreiffer (BCS) theory of superconductivity in 1957 (*Science*, 3 November 1972), several physicists extended to BCS theory (in which electrons in metals form pairs) to the pairing of helium-3 atoms.

New phase transitions in helium-3 were found in 1972 by Douglas Osheroff, Robert Richardson, and David Lee of Cornell (*1*). The early experiments did not show helium-3 was superfluid, but identified unusual phases of the liquid at a few millidegrees Kelvin (mK).

A very recent experiment by O. V. Lonasman, Yu. D. Anufriyev, and colleagues at the Helsinki University of Technology, Finland, has buttressed the superfluid hypothesis by showing that at temperatures below 2.65 mK helium-3 seems to behave like a combination of two fluids (*2*). By measuring the damping of a wire vibrating in liquid helium-3, the Finnish group showed that the interaction of the wire with the fluid decreased slightly at the first transition (2.65 mK) and decreased drastically at the second. Although the experiment did not directly show that the viscosity of the superfluid dropped to zero, it appears to strongly substantiate the suggestion that both normal fluid and superfluid are present below 2.65 mK, but only the normal fluid has viscosity. If more and more superfluid is formed as the liquid is cooled, then the density of normal fluid in the cell will decrease, and the greatly reduced damping of the wire can be explained. A similar "two fluid theory"—a theory that helium in its superfluid phase is composed of a superfluid component and a normal fluid component—has been very successful in explaining the properties of helium-4 after it "condenses."

Many experiments have been needed to construct a diagram of the various phases of helium-3 (Fig. 1). The original discovery of new phase transitions in liquid helium-3 was made when the liquid was being compressed at a constant rate to form a solid. At a pressure of 33.9053 atm the rate of pressurization decreased, and at a pressure of 33.9279 atm the pressure actually dropped by about 3×10^{-4} atm. Both features are quite reproducible, and the two transitions, which are called simply A and B because no one understands them very well, occur at temperatures of 2.65 mK and about 2 mK. The method for cooling helium-3 was to first cool the liquid below 300 mK by conventional techniques and then to compress it. The temperature of solidification of helium-3 at a certain pressure is uniquely characteristic of it and defines a "melting curve." (At temperatures above about 320 mK, where there is a minimum in the melting curve, this technique would result in heating rather than cooling.) The original experiment determined the temperatures of the A and B transitions only at pressures along the melting curve.

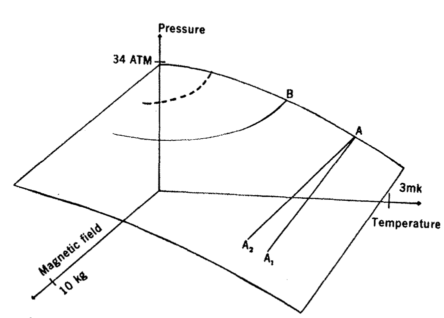

Fig. 1. A diagram of transitions between various phases of helium-3 at temperatures near absolute zero. The letters A and B indicate transitions from one liquid phase to another. The dashed line may be a transition from one solid phase to another.

Because both liquid and solid helium were present in the helium-3 cell in the original experiment, it was difficult to determine which one had changed phase. (The solid was expected to change from a state with disordered spins to one with ordered spins, while still remaining solid.) In fact, the original interpretation of the experiment was that a new solid phase had been found. However, further experiments measuring the nuclear magnetic resonance (NMR) and specific heat of the different phases have conclusively established that both A and B represent changes from one liquid phase to another.

Because helium-3 has a nuclear spin, a magnetic field strongly influences its phase transitions, and measurements of the strength of its nuclear magnetic resonance provide a powerful tool for analyzing many properties. Helium-3 may be the first magnetic superfluid. Lee and associates at Cornell placed a small radio frequency coil inside a helium-3 cell and applied a magnetic field that varied smoothly across the cell (*3*). Since the nuclear spin of helium-3 resonates at a different frequency for different field strengths, it was possible to see what was happening from the bottom of the cell to the top by sweeping through a range of radio frequencies. What Lee, Richardson, and associates found was that the solid helium-3 forms primarily at the bottom of the cell. During the cooling most of the helium-3 at the top of the cell remains liquid, and the NMR response of the liquid changes at both the A and B transitions.

John Wheatley, Richard Johnson, and associates at the University of California, La Jolla, confirmed the idea that strange phase transitions were occurring in liquid helium-3 by showing that the slope of the melting curve did not change appreciably at the A transition (*4*). If the solid were changing from a state with disordered spin to one with ordered spin (an antiferromagnetic state was expected), the large entropy change would have been reflected in a change of the melting curve slope. Furthermore, Wheatley and his associates prepared samples of purely liquid helium-3 by a technique different from compressional cooling and measured the specific heat change of the A transition over a range of pressures corresponding to a region below the melting plane in Fig. 1 (*5*). At the A transition the specific heat has a discontinuity, as it does in the transition from a normal conductor to a superconductor (a second-order phase transition with no divergence of the specific heat). This measurement substantiates the idea that pairing of the BCS type is taking place at the A transition, and that the phase change is different from the Bose-Einstein "condensation" that occurs when helium-4 becomes superfluid (the specific heat of helium-4 does diverge when it becomes superfluid).

The NMR experiments of the researchers at Cornell give more detail about the sort of pairing that takes place in helium-3. If the spins of pairs of helium-3 atoms coupled in such a way that they canceled (antiparallel), the NMR signal would decrease at the A transition. But the signal doesn't decrease, so the spins must be coupling parallel to each other. The A transition of liquid helium-3 appears to be the first example of such pairing (with total spin 1) and thus requires a generalized form of the BCS theory. In a superconductor, the pairs of electron spins are antiparallel (total spin zero). While the NMR signal doesn't decrease, it shifts to successively higher frequencies as the liquid is cooled. The pairs of helium-3 atoms with parallel spins have magnetic properties of their own, and they apparently produce an effective magnetic field in the liquid that causes the frequency shift. In anti-parallel pairing all the magnetic moments would cancel, and no such internal field would result. Phillip W. Anderson of the Bell Telephone Laboratories, Murray Hill, New Jersey, has made extensive studies of theories of pairing in helium-3, and Anthony J. Leggatt of the University of Sussex, has given a detailed theory of the frequency shift. At the temperature of the B transition the shift disappears, and the NMR signal amplitude decreases by about 50 percent.

Both transitions A and B occur at different temperatures when a magnetic field is applied to liquid helium-3. The B transition moves so rapidly toward lower temperatures that formation of the B phase may not be possible for magnetic fields greater that 5 kilogauss. According to Robert Richardson, at Cornell, the A transition splits into two transitions occurring at different temperatures when a magnetic field is applied to liquid helium-3 (the two transitions are indicated by letters A_1 and A_2 in Fig. 1). The splitting was observed by repeating the original measurements that led to the discovery of the A transition in a magnetic field, and by measuring the attenuation of sound in liquid helium-3. Most experimentalists studying helium-3 now believe that the two transitions, A_1 and A_2, occur as the helium-3 pairs with spins "up" and "down" successively undergo pairing. Thus, the different properties of the two fluids are only apparent in a magnetic field, which defines an up and down direction. So far, no theoretician has predicted which pair undergoes the transition first.

Unanswered Questions about Helium-3

The nature of the liquid phase at temperatures below the B transition is not so well understood as the liquid phase between A and B. According to David Lee, the B transition is probably a first-order one, because hysteresis is observed in the pressurization curve, but first-order transition properties have not been well established. The liquid at temperatures below the B transition may undergo a further change in the spin state of helium-3 pairs to produce a highly symmetric state (such as a state with spin projection $M_z = 0$).

The study of helium-3 is in its infancy, and many questions are still to be answered. For instance, where is the solid transition (to an antiferromagnetic state)? Recently William Halperin and other members of the Cornell group appear to have found a reproducible feature in the pressurization curve at a pressure about 30 millibars higher than that of the B transition. The temperature corresponding to this pressure is not well known, but is estimated to be about 0.5 mK. But most experimentalists agree that more study is needed to tell whether a transition has been found.

Many other questions still cannot be answered about the liquid phases. Even though the Helsinki experiment suggests that something very dramatic is happening to the flow properties of helium-3, it has not yet been proved to be superfluid. Most experimentalists probably believe that a superfluid is really present, but some other explanation may suffice—a liquid crystal transition was suggested to explain the anomalous changes of viscosity in the early stages of research on helium-4. The nature of the fluid produced in the B transition is not at all well understood. Neither is it known yet whether the A and B fluids become indistinguishable at some critical pressure. (Wheatley and his coworkers see preliminary indications of a transition that merges with the A transition at pressures below the melting curve.) So far the properties of solid helium-3 at temperatures of a few millidegrees have been almost completely neglected.

The phase diagram alone shows that helium-3 is a rich and complex problem. Within a few millidegrees, two solid phases and four liquid phases—in all likelihood—are to be found. In contrast, helium-4 has only two liquid phases (as far as anyone knows), and the influence of a magnetic field is not even relevant. Yet the study of helium-4 has repeatedly challenged the ingenuity of experimental physicists for the last 30 years, and many of the most gifted physicists of the era have grappled with the theory of the substance, which is one of the few macroscopic examples of quantum phenomena.

If the early promise of helium-3 research is not misleading, the peculiar behavior of this strange substance may fascinate another generation of scientists.—WILLIAM D. METZ

References

1. D. D. Osheroff, R. C. Richardson, D. M. Lee, *Phys. Rev. Lett.* **28**, 885 (1972).
2. T. A. Alvesalo, Yu. D. Anufriyev, H. K. Collan, O. V. Lounasmaa, P. Wennerstrom, *ibid.*, to be published May 14, 1973.
3. D. D. Osheroff, W. J. Gully, R. C. Richardson, D. M. Lee, *ibid.* **29**, 920 (1972).
4. R. T. Johnson, D. N. Paulson, C. B. Pierce, J. C. Wheatley, *ibid.* **30**, 207 (1973).
5. R. A. Webb, T. J. Greytak, R. T. Johnson, J. C. Wheatley, *ibid.*, p. 210.