HELIUM, THE UNRULY LIQUID

Liquid helium creeps up over the walls of its container, conducts heat better than any other substance, and exhibits other strange properties. How this can be used as a key to the quantum behavior of matter is explained by an authority in the field of low-temperature physics.

*by **Laszlo Tisza***

The behavior of liquid helium is so unusual that it is not unreasonable to consider it the only representative of a fourth state of matter; helium gas condenses not into the liquid state, but rather into the quantum liquid state. Liquid helium is thus unique in low temperature physics; it is important both in the techniques of producing low temperatures and for its peculiar properties.

Historically the physics of low temperatures originated in attempts to liquefy what were then called 'permanent' gases because persistent efforts to liquefy them had failed for a long time. Even now, low temperatures are produced by liquefying these gases. Using liquid air, one can reach approximately 70°K (the equivalent of − 203° on the Centigrade scale, whose zero point is 273 degrees higher than that for the Kelvin, or absolute scale, a temperature scale more convenient in cryogenics, the trade name for low temperature physics). With liquid hydrogen one can go down to about 15°K, and with liquid helium down to 1°K, one degree above absolute zero. Liquefying helium is an indispensable step in going below about 15°K.

properties of helium II were suggested by theory, and this seems to be the right point to outline a few relevant theoretical ideas.

Why?

The theory proceeds by advancing a few fundamental assumptions about the properties of helium, the first of which is that, in its zero entropy state, helium II behaves as an ideal liquid or a superfluid. The meaning of this statement is that the molecular mechanisms usually responsible for viscous drag are absent. In ordinary substances there are two kinds of viscosity which can be clearly identified by their dependence on temperature. The viscosity of liquids is due to a sort of 'stickiness' owing to intermolecular forces; we call it dynamic viscosity. An increase in temperature makes the liquid less 'sticky' and the dynamic viscosity decreases. In contrast to this the viscosity of gases is due to the thermal motion. We call it kinetic viscosity, and note that it increases with increasing temperature.

The superfluidity of helium at absolute zero implies that at finite temperatures dynamic viscosity is not effective though it is a liquid, and its viscosity is kinetic, like that of a gas, furthermore the kinetic viscosity tends to zero with temperature.

The absence of dynamic viscosity can be qualitatively explained using the quantum mechanical concept of zero point motion which blows up the volume of the liquid to about threefold the value it would have if the atoms were closely packed. The atoms are too far away to 'lock' each other's motion, hence: no freezing and no dynamic viscosity results. Whether or not this explanation is convincing, the absence of dynamic viscosity is an experimental fact, and we can safely build our conclusions on this premise.

Turning now to the discussion of the kinetic viscosity, we have to make some assumption concerning the nature of thermal agitation in helium. We will assume that the thermal agitation, which exists in addition to the zero-point motion, is of the same type as that of an ideal gas. If this is true, this gas will have to be a Bose-Einstein gas, since helium atoms contain an even number of elementary particles. When first suggested, this assumption was considered very bold, since the details of the Bose-Einstein statistics have been worked out only for ideal gases and it was not clear to what extent these results would stay valid for the system of interacting helium atoms. Whatever may be the form of the theory ultimately accepted, the Bose-Einstein hypothesis proved to be extremely fruitful.

According to these ideas, the lambda point in helium is interpreted as the condensation temperature of the Bose-Einstein gas mentioned above. Above the lambda point we have helium I which possesses a kinetic viscosity. Below the lambda point we have helium II, which behaves as a partially condensed Bose-Einstein gas and is a mixture of two components: one with, the other without thermal agitation. The first one will have a kinetic viscosity, the second no viscosity at all: it is superfluid.

According to the resulting picture helium II is a mixture of a superfluid liquid and a viscous 'gas.' The concentration of the mixture remains constant for processes where there is no heat exchange but absorption of heat has the effect of increasing the concentration of the viscous component at the expense of the superfluid, and vice versa.

The hydrodynamical properties of such a mixture are quite complex, but they are flexible enough to explain things which appear paradoxical in ordinary hydrodynamics. The important point is that the superfluid and viscous components may have different flow velocities, giving rise to an 'internal convection' which is connected with an energy transfer without any mass transfer. This internal convection accounts for the super heat-conductivity.

The phenomena in thin capillaries are explained by the fact that the flow of the viscous component is effectively stopped in very thin capillaries while the superfluid component can flow unhindered. Thus such capillaries behave like semipermeable membranes. The fountain effect is interpreted like osmosis: the heating increases the concentration of the viscous component and also the osmotic pressure and the superfluid component is sucked into the cell.

The theory led also to the prediction that the complex hydrodynamics could be best studied by observing wave phenomena, of which there are two types in helium II. The first is identical to ordinary sound waves: for this kind of motion the velocities of the superfluid and viscous components are equal and in phase. The second type is characteristic of helium II; it is called second sound or temperature wave. In this case the flow velocities of the two components are always opposite to each other. Second

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sound can be excited by means of periodical heating of a solid wall in contact with helium II. The second sound has actually been observed by Peshkov in Moscow and by Lane and collaborators at Yale University. The velocity of propagation as a function of temperature is in good agreement with the theoretical prediction.

Whereas the experimental evidence in favor of the complex hydrodynamics is overwhelming, its foundation on the Bose-Einstein statistics is less certain. Actually, several other theories have been put forward, the common feature of which is that they do not admit any connection between the superfluidity of helium and the Bose-Einstein statistics. Although these theories lead to more or less similar conclusions as the Bose-Einstein theory, an experimental decision of their relative merit is possible, owing to the existence of a helium isotope of the atomic weight 3, which obeys Fermi-Dirac statistics. If the Bose-Einstein statistics is essential for the superfluidity of the abundant isotope He^4, then He^3 should be not superfluid and a separation of the two isotopes by capillary flow should be possible. On the other hand, according to the other theories, no essential difference can be expected for the two isotopes.

Since He^3 is present in ordinary helium only as one part in ten million, experiments are difficult. Nevertheless, preliminary experiments of this kind have been recently carried out by Daunt and by Lane and their coworkers. These experiments indicate that He^3 is not superfluid and thus seem to justify the connection of Bose-Einstein statistics with superfluidity.

If the separation of He^3 in sizable amounts is indeed possible, the study of this substance would be of considerable interest. It would be the only case where two stable isotopes have radically different properties. It seems very likely that He^3 cannot exist in the liquid state at all. Such a liquid should have a vanishing dynamic viscosity and a high kinetic viscosity. Either we will have a liquid of entirely unheard-of properties, or the system will avoid the dilemma of the small and large viscosities by not liquefying at all, but will either freeze or rather stay a gas at vanishing pressure and temperature. It is to be hoped that the experimental decision of this question will be forthcoming before long.

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less aimless and would, on the other hand, demand all his energies and enthusiasm, this sense of significance and urgency, sadly lacking today, might be achieved.

The opportunity to take part in the building and the developing of one of science's most important machines gave to a group of four students the inspiration to pour all their intellectual vigor and enthusiasm into an undertaking few people would have thought possible. They worked diligently and seriously, but not from any external compulsion. Rather, confronted by a challenge which excited their intelligence, imbued with the importance of the nature of the venture, these boys brought to their project all the ability, resourcefulness, and initiative of which they were capable. They labored zealously after school hours and on holidays and weekends, manifested surprisingly mature leadership, and displayed a healthy readiness to accept responsibility.

The daring work of these students of El Cerrito High School has attracted attention on an international scale. Following newspaper accounts of their efforts, letters have come from all over the world—from individuals, high schools, colleges and universities—asking for plans and advice on the construction of the cyclotron. A steady stream of visitors still continues to come to see the machine. Three visiting Chinese physicists were so impressed that they requested permission to build an exact replica. Recently, a visiting professor of nuclear physics from the University of Calcutta, who built the first cyclotron in India (39 inches), spent a few afternoons of his precious time working with the students on their machine. He felt, he said later, that he had gained a great deal from this experience. He would return to India to tell the students there of what was within the realm of their capacity, if they would apply themselves.

The Research Corporation of New York City, which holds the patent rights to the cyclotron, as an assignee of Dr. Lawrence, has granted the high school science department a royalty-free license "to practice the art of this patent, for educational, scientific, experimental and research purposes." The educational and scientific aspects are presently being thoroughly treated. The experimental and research work, it is expected, will be undertaken seriously in the near future.