

## CHAPTER I

## INTRODUCTION

**1.1. The liquefaction of helium**

Helium is the most difficult of all the permanent gases to liquefy. This is a consequence of the weakness of the attractive forces between helium atoms, for condensation into a liquid can occur only when the forces holding the liquid together are strong enough to overcome the disruptive influence of thermal agitation, and this is the case for helium only if the temperature is within a few degrees of the absolute zero. The critical temperature is  $5.20^\circ\text{K}$ . and the boiling-point is  $4.21^\circ\text{K}$ .

The  $\text{He}^4$  atom is a particularly simple, stable and symmetrical structure. The nucleus contains two protons and two neutrons and has no resultant angular momentum or magnetic moment. The two extranuclear electrons completely fill the innermost *K* shell and, being so close to the nucleus, are firmly bound. The ionization potential of  $24.56$  volts is greater than that of any other atom and transitions between atomic energy levels are not likely to be important at temperatures less than about  $10^5$  °K. The atom has no electric or magnetic dipole moment and its electric polarizability is very small. It is the last fact which explains the weakness of the interatomic forces, for van der Waals' forces are now known to be directly related to the electric polarizability of the atom, which, in its turn, depends upon the separation of the energy levels of the electrons, so we can see a direct connexion between the low boiling point of liquid helium and the high excitation energy of the helium atom.

We might therefore expect the helium atom to be the nearest approximation to the hard sphere of classical kinetic theory and liquid helium might seem the simplest liquid to investigate in order to discover the fundamental principles of the theory of the liquid state. In actual fact the behaviour of liquid helium is so remarkable that it presents an intriguing problem which is unique in physical theory. The reason for this is almost certainly con-

nected with the low temperature of the liquid and the possibility that certain quantum effects are able to manifest themselves at such a low temperature. F. London has therefore described it as a 'quantum liquid'.

The first successful liquefaction was accomplished by Kamerlingh Onnes (1908). Helium was found to give a colourless, transparent liquid with a density about one-seventh of that of water. Solid helium cannot be made merely by reducing the temperature of the liquid, as is the case for all other substances. Liquid helium in contact with its vapour has often been reduced to temperatures as low as  $0.1^\circ\text{K}$ . without solidifying, and it is probable that the liquid still exists at the absolute zero. The solid can be produced only by applying a pressure of the order of 25 atmospheres. Simon (1934) has shown that this is a consequence of the large zero-point energy of the liquid and it is the first of the quantum effects that we shall have to consider.

### 1.2. The $\lambda$ -transition

At  $2.18^\circ\text{K}$ . liquid helium undergoes a transition which may be demonstrated in the following spectacular way. Liquid at the boiling point can be cooled by reducing the pressure above its surface with a vacuum pump. During this pumping the high temperature modification, liquid helium I, boils vigorously and is clouded by a mass of small bubbles, but suddenly, as soon as the transition temperature is reached, the boiling stops abruptly and the low temperature modification, liquid helium II, appears as a transparent, quiescent liquid which refuses to boil. Liquid helium II has many unusual properties, one of which is a very high thermal conductivity (under some circumstances more than 1000 times greater than that of pure copper at room temperature) and this is the cause of the absence of boiling. If a bubble forms below the surface of a liquid, the pressure inside the bubble must be greater than the vapour pressure above the surface by the hydrostatic pressure head plus the surface tension pressure. Vapour at this increased pressure cannot be formed from the liquid unless the temperature is higher than the temperature at the surface by an amount determined by the slope of the vapour pressure curve. The thermal conductivity of liquid helium II is so large that such

a temperature difference cannot be set up, and so boiling is prevented and all the evaporation takes place at the surface.

The transition from liquid helium I to liquid helium II involves no latent heat and no discontinuous change in volume, so it is not a first order transition with discontinuities in the first derivatives of the Gibbs free energy. In § 2.6 we shall discuss this in more detail and shall explain why we prefer not to describe the transition as 'of the second kind' or 'of the second order'. The term  $\lambda$ -transition is non-committal and arises from the resemblance between the Greek letter  $\lambda$  and the shape of the specific heat versus temperature curve. The transition temperature is referred to as the  $\lambda$ -point.

### 1.3. Superfluidity and the two-fluid theory

The most remarkable of the properties of liquid helium II is its 'superfluidity', which was discovered simultaneously by

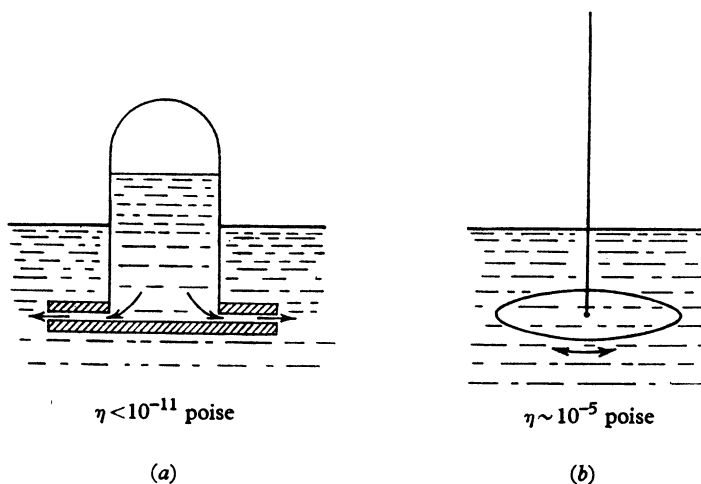


Fig. 1. The two different methods of measuring the viscosity of liquid helium II. (a) Flow through narrow channels; (b) damping of an oscillating disk.

Kapitza (1938) and by Allen and Misener (1938*a*). Fig. 1*a* illustrates the type of experiment performed by Kapitza. A very narrow gap, with a width between  $10^{-5}$  and  $10^{-4}$  cm., can be made by pressing together two optically polished glass surfaces. Liquid helium II flows through such a gap with a velocity of many centimetres per sec., corresponding to an effective viscosity of less than

$10^{-11}$  poise, which should be compared with  $10^{-2}$  poise for water,  $2 \times 10^{-5}$  poise for liquid helium I and  $5.5 \times 10^{-6}$  poise for helium gas at  $1.64^\circ \text{K}$ . However, further investigation reveals that the flow is almost independent of the pressure head and varies in a complicated way with the width of the gap, so a coefficient of viscosity is not relevant to the phenomena. Moreover, if the viscosity is estimated by observing the damping of the torsional oscillations of a disk immersed in the liquid (fig. 1*b*), then, as long as the peripheral velocity of the disk is not too great, the behaviour is that of a normal liquid and the viscosity has a much larger value, of the order of  $10^{-5}$  poise.

The solution of this dilemma is provided by the two-fluid theory originated by Tisza (1940) and developed in a slightly different form by Landau (1941). The liquid is considered to be some sort of intimate mixture of two components, a normal component and a superfluid component, so that its total density  $\rho$  can be separated into a normal density  $\rho_n$  and a superfluid density  $\rho_s$

$$\rho = \rho_n + \rho_s. \quad (1.1)$$

The normal component is assumed to have a normal viscosity and is therefore responsible for the damping of the motion of an oscillating disk and the relatively high value of the apparent viscosity deduced from this damping. The superfluid component, on the other hand, is the part capable of flowing through very narrow channels with high velocities, and it is presumably subject to very little viscous retardation.

This division into two components was demonstrated in a very convincing manner in an experiment performed by Andronikashvili (1946). A pile of disks performed torsional oscillations in the liquid (see inset to fig. 2). The gap between the disks (0.21 mm.) was sufficiently small so that, above the  $\lambda$ -point, all the liquid between the disks was dragged round with them and contributed to the effective moment of inertia of the system. Below the  $\lambda$ -point, however, only the normal component moved with the disks, the superfluid component being subject to no frictional force which would have brought it into motion. Therefore, as the temperature was lowered below the  $\lambda$ -point, the period of oscillation steadily decreased and it was possible to deduce from it the fraction  $\rho_n/\rho$

of liquid contributing to the moment of inertia of the system. The results are shown in fig. 2, from which it will be seen that the fraction of normal liquid,  $\rho_n/\rho$ , steadily decreases below the  $\lambda$ -point, while the fraction of superfluid,  $\rho_s/\rho$ , builds up from zero at the  $\lambda$ -point to unity at  $0^\circ$  K.

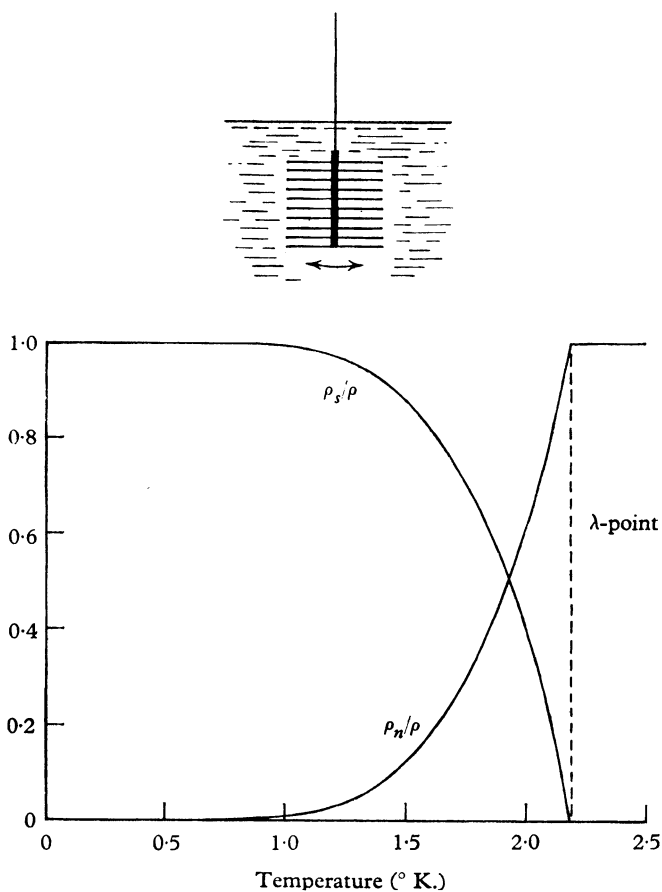


Fig. 2. Andronikashvili's experiment.

The two-fluid theory is now an essential part of the modern approach to the liquid helium problem and will be tacitly assumed throughout the rest of this monograph. It is possible, of course, that a complete theory of liquid helium will reveal that the two-fluid hypothesis is only a first approximation. However, for pur-

poses of exposition, the concept of a mixture of superfluid and normal components is very convenient and is certainly adequate to describe the present state of theory and experiment.

#### 1.4. The liquid helium film

Any surface dipping into liquid helium II is covered by a film which is about  $3 \times 10^{-6}$  cm. thick at a height of 1 cm. above the surface of the bulk liquid. This film was first postulated by Rollin (1936) to explain an anomalous heat flow into a special type of cryostat, but its properties were first elucidated in a series of experiments performed by Daunt and Mendelssohn (1939*b*), and the rest of this section will be devoted to an exposition of their pioneer work. In one of their experiments they dipped an empty beaker

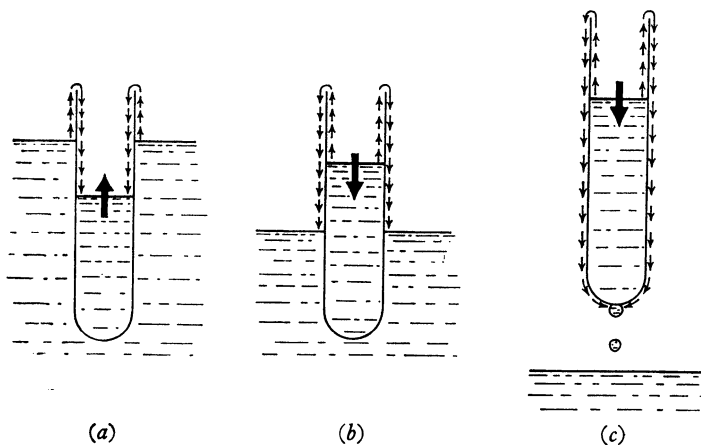


Fig. 3. Pioneer film flow experiments of Daunt and Mendelssohn. (a) Beaker filling through the film; (b) beaker emptying through the film; (c) drops forming on the bottom of the beaker.

into a bath of liquid helium II (fig. 3*a*) and observed that it gradually filled with liquid until the levels were equal inside and outside, presumably because superfluid flow was able to take place through the film on the wall of the beaker. When the beaker was raised, flow occurred in the opposite direction and the inside level slowly fell down to the outside level (fig. 3*b*). When the beaker was lifted completely out of the bath, it slowly emptied itself and drops of liquid could be seen forming on its bottom and dripping into the bath (fig. 3*c*).

As we shall see in chapter 4, superfluidity is most clearly manifested in flow through very narrow channels and the film presents us with an extremely narrow channel. The phenomena associated with film flow have therefore been taken to indicate the nature of 'ideal superfluidity'. The most outstanding aspect of film flow is that the rate of flow is almost independent of the pressure head or the length of the film. Fig. 4 shows the results of measurements by Daunt and Mendelssohn on the rate of emptying of a long beaker. Apart from a small region near the rim, the rate of transfer was

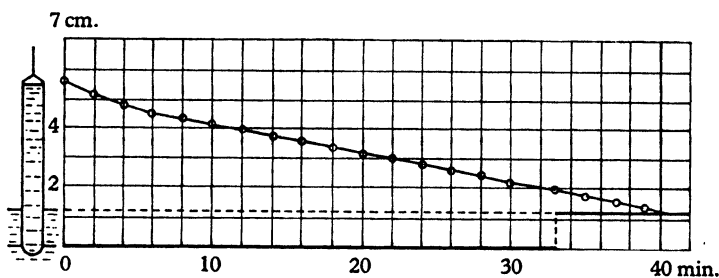


Fig. 4. Almost constant rate of film transfer from a long beaker (after Daunt and Mendelssohn, 1939*b*).

constant to within 20% throughout the whole length of the beaker. This has led to the concept of a critical velocity  $v_{s,c}$ . It seems that the film is rapidly accelerated up to this velocity but that some mechanism then operates to prevent any further acceleration. Writing  $d$  for the thickness of the film and assuming that the transfer is due to flow of the superfluid component with a density  $\rho_s$  (provisionally assumed to be the same as  $\rho_s$  in the bulk liquid), then the rate of transport of mass per unit length of the perimeter over which the film flows is

$$\rho_s v_{s,c} d \text{ g. sec.}^{-1} \text{ cm.}^{-1}.$$

The critical rate of transfer,  $\sigma_c$ , is normally defined in terms of the volume of bulk liquid transferred to or from the inside of the vessel and is therefore

$$\sigma_c = \frac{\rho_s}{\rho} v_{s,c} d \text{ cm.}^3 \text{ sec.}^{-1} \text{ cm.}^{-1}. \quad (1.2)$$

This concept of a critical velocity receives support from the fact that the rate of transfer is determined by the perimeter of the

## LIQUID HELIUM

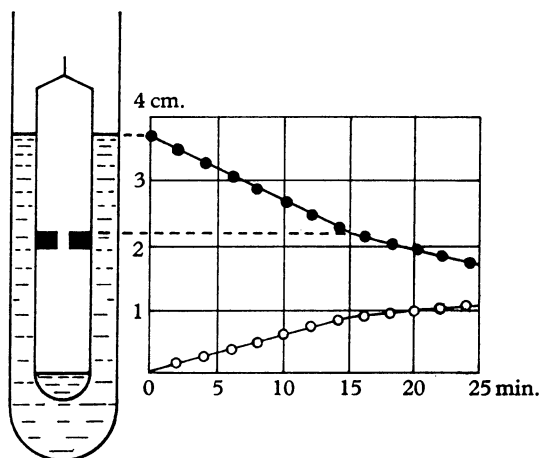


Fig. 5. Influence of a constriction on film flow (after Daunt and Mendelssohn, 1939*b*). ●, outer level; ○, inner level.

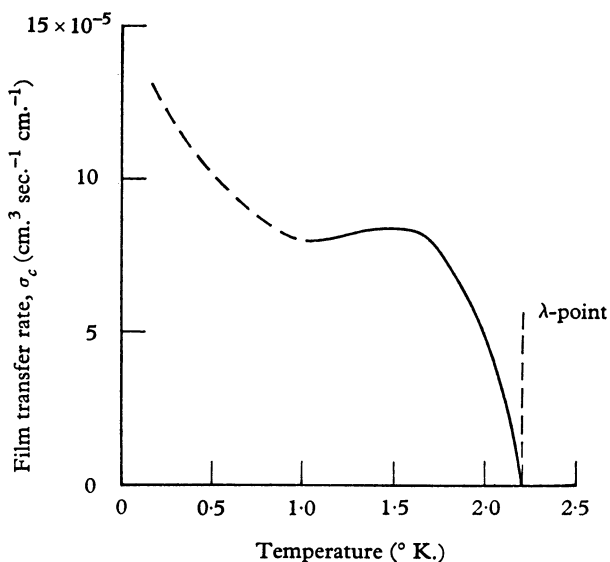


Fig. 6. Rate of transfer through the helium film as a function of temperature.

narrowest constriction higher than the upper liquid level. This was demonstrated with the apparatus of fig. 5. As long as the outer level was above the constriction the rate of transfer was determined by the inside diameter of the beaker, but as soon as the outer level fell below the constriction, the rate of transfer was reduced in



exact proportion to the ratio of the perimeter of the constriction to the inside perimeter of the beaker.

The critical rate of transfer,  $\sigma_c$ , is shown as a function of temperature in fig. 6. Much of this temperature variation is no doubt due to the factor  $\rho_s/\rho$  in equation (1.2), but  $v_{s,c}$  and  $d$  may vary with temperature also. Moreover, the later experiments to be described in chapter 7 indicate that the situation is quite complicated and the ideas presented in this section may have to be considered as only a first approximation.

### 1.5. Thermal effects

The flow of liquid helium II is accompanied by some unusual thermal effects, all of which may be explained by the assumption that

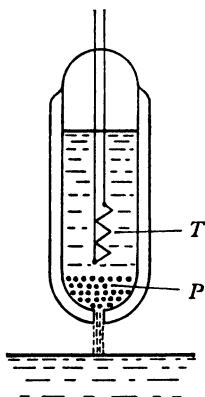


Fig. 7. Apparatus to demonstrate the mechanocaloric effect (after Daunt and Mendelssohn, 1939*a*).

the total entropy of the liquid is associated with the normal component only, and that the superfluid component is entirely devoid of entropy and behaves, in a certain sense, like a liquid at  $0^\circ\text{K}$ . This is directly obvious in the *mechanocaloric* effect predicted by Tisza (1938) and discovered by Daunt and Mendelssohn (1939*a*). A Dewar vessel (fig. 7) was able to empty itself through a small orifice packed with fine emery powder  $P$ . As the liquid flowed out of the vessel the temperature of the remaining liquid, recorded by the phosphor bronze resistance thermometer  $T$ , rose by about  $0.1^\circ\text{K}$ . The interpretation is that only the superfluid component was able to flow through the narrow channels between the grains of emery

powder and so the liquid flowing out left all its entropy behind to warm up the liquid remaining inside.

The *thermomechanical* effect or 'fountain effect' was discovered by Allen and Jones (1938). The vessel of fig. 8*a* was connected to the bath via a fine capillary. When heat was supplied to the inside of the vessel the inner level rose and took up a steady position well above the bath level. Presumably the superfluid component, being

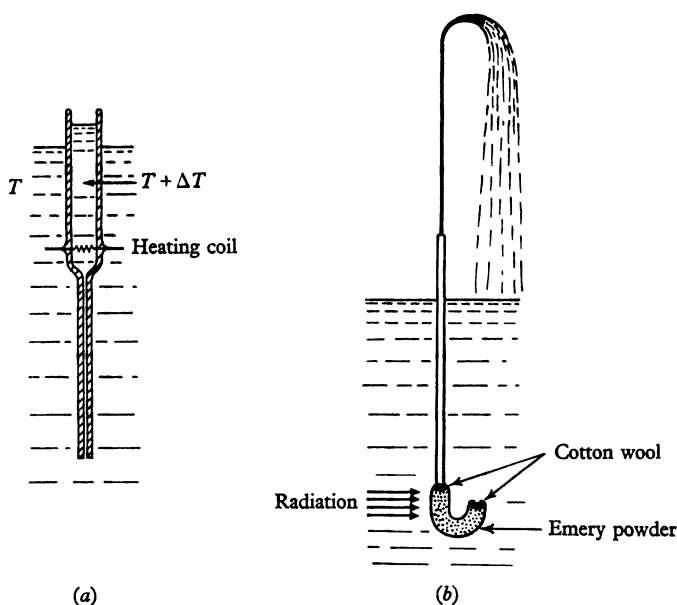


Fig. 8. (a) The thermomechanical effect; (b) the liquid helium fountain (after Allen and Jones, 1938).

cold, has a tendency to move towards regions of higher temperature and therefore flowed into the vessel until the pressure gradient forcing it out again was large enough to counterbalance the temperature gradient forcing it in. A rather pretty demonstration of this effect can be given with the apparatus of fig. 8*b*. Liquid can enter the inside of the vessel only through the packed emery powder. When a light is shone on to the apparatus the black powder absorbs heat, the inside temperature rises and the liquid rushes in with such force that it emerges from the nozzle to form a fountain which can be as much as 30 cm. high.