52.11: Superfluids

When liquid helium-4 ($^{4}\mathrm{He}$) is cooled below a critical temperature of $2.17\ \mathrm{K}$ (called the lambda point), a sudden phase transition occurs, and the helium becomes an exotic fluid called helium II. [5] Helium II is the best-known example of a superfluid — a fluid with odd properties that are governed by the laws of quantum mechanics.

As helium I is cooled toward the lambda point, it boils violently; but when the lambda point is reached, the boiling suddenly stops. This is due to a sudden increase in the thermal conductivity of the liquid when it transitions to the superfluid state. The thermal conductivity of superfluid helium II is more that a million times greater than that of liquid helium I, and helium II is a better conductor of heat than any metal.

Superfluid helium II is perhaps best known for its unusual viscosity. One method for measuring the viscosity of a liquid is to allow it to flow through a thin tube or channel called a capillary: the more viscous the liquid, the larger the diameter of the capillary needed to permit the liquid to flow. Helium II can flow through capillaries much less than $1 \mu\mathrm{m}$ in diameter, and in such experiments behaves as though it has zero viscosity. This ability of helium II to flow through very tiny capillaries is called superflow.

Another method for measuring viscosity is to rotate a small cylinder inside the liquid; viscosity will cause the liquid to be dragged along with the cylinder, and a small rotatable paddle placed near the axis of the rotating cylinder will show whether the rotating cylinder is causing the liquid to rotate. In such experiments, helium II does exhibit some viscosity. No ordinary liquid exhibits this sort of dual behavior with respect to viscosity.

A common model to explaining this odd behavior is called the two-fluid model. In this model, liquid helium II is thought of as consisting of two interpenetrating components: a normal (viscous) component, and a superfluid (nonviscous) component. In the capillary experiment, only the superfluid component flows through the tiny capillaries, but in the rotating-cylinder experiment, the normal component is dragged along with the cylinder, causing circulation in the liquid.

Another unusual phenomenon observed in helium II is called the fountain effect (Fig. $52.11.1$). A tube with a porous plug in the bottom is placed inside a bath of helium II. A superflow of helium is observed to flow through the tiny ($\ll 1 \mu\mathrm{m}$) capillaries toward the heater; upon being heated, the superfluid component is converted to a normal component, and the fluid is unable to flow back out through the fine capillaries in the plug. Pressure builds in the tube until the helium squirts out of the capillary in the top of the tube, creating a "helium fountain". Since the second law of thermodynamics states that heat cannot flow from lower to higher temperatures, this implies that the superfluid component carries no heat: any heat in the helium II must be in the normal component.

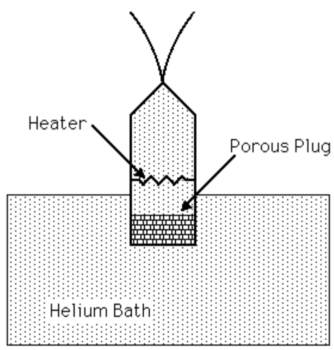

Figure $52.11.1$: The fountain effect in superfluid liquid helium II. (Credit: NASA.)

Yet another interesting property of helium II is the formation of a very thin film called a Rollin film when the liquid is placed in a container. The Rollin film will creep up the sides of the container, and if the container is open, it will creep back down the outside, so that the helium II will spontaneously creep out of the container(Fig. $52.11.2$). The Rollin film is much less than $1 \mu\mathrm{m}$ in thickness; its creeping speed is slow just below the lambda point, but may reach a speed as high as $35\ \mathrm{cm/s}$ at lower temperatures.

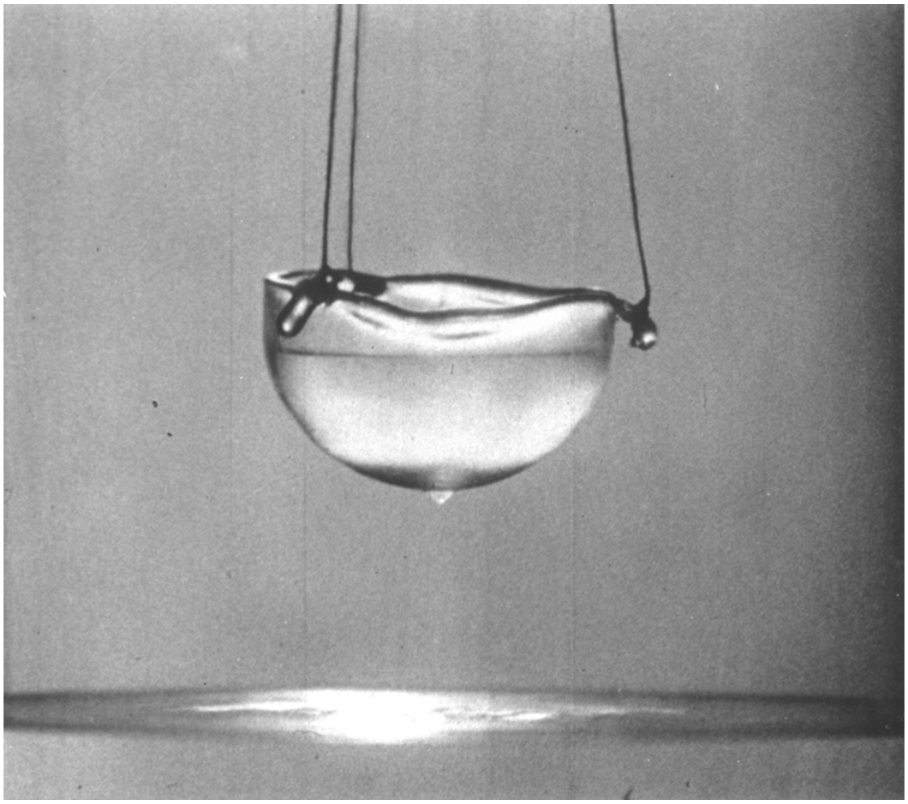

Figure 52.11.2: A Rollin film of superfluid helium II. The film creeps up the sides of the container and back down the outside, collecting in small drops at the bottom. (Credit: Liquid Helium II: The Superfluid, University of Michigan.)

Finally, helium II exhibits an unusual way of conducting heat. Normally, substances conduct heat through diffusion, where the rate of heat flow is proportional to the temperature difference; but in superfluid helium II, heat is conducted by waves. This phenomenon is called second sound, and no other substance exhibits this behavior. The speed of second sound is small just below the lambda point; at a lower temperature of $1.6\ \mathrm{K}$, it is about $20\ \mathrm{m/s}$.

It should be kept in mind that the two-fluid model of helium II discussed here is simply a model-a convenient way of thinking about the behavior of the liquid. Superfluid helium II is a quantum liquid, and a complete description of its behavior requires the application of quantum mechanics.

---

5. Above $2.17\ \mathrm{K}$, liquid helium is a (mostly) ordinary liquid called helium I.
