

THE DISCOVERY OF SUPERFLUIDITY

Two of the greatest physics discoveries in the first half of the 20th century were superconductivity and superfluidity.¹ Superconductivity involves the frictionless conduction of electricity in wires, and superfluidity the frictionless flow of superfluid liquid helium through channels. Both discoveries led to the arcane phenomenon of macroscopic quantization: the manifestation of the laws of quantum mechanics not just on atomic dimensions but also on the scale of common laboratory apparatus. Both discoveries required the liquefaction of helium, which was first done in 1908.

Superconductivity was discovered almost immediately after liquid helium became available—by 1911—and its importance in the construction of magnets was quickly recognized.² Although there were hints as early as 1911 that something was peculiar about liquid helium near 2 K, it was not until 1938 that superfluidity was discovered and named. (Figure 1 is a remarkable photograph of a superfluid-helium fountain, one of the hallmarks of superfluidity.) Analogies between the two phenomena played an important part in the discovery. Why was it that these closely related discoveries occurred more than a quarter of a century apart? No technical barrier stood in the way of the discovery of superfluidity, and as we shall see, suggestions of a new phenomenon were definitely present.

Liquid helium

Helium was not discovered on Earth. It was found in the spectrum of light from the Sun during a total solar eclipse visible in India in 1868.³ The French astronomer Jules Janssen, equipped with a spectroscope, observed a yellow line in the spectrum of light from the Sun, which he correctly attributed to the radiation from a chemical element not heretofore observed on Earth. Janssen's discovery was confirmed by Joseph Norman Lockyer, who proposed the name "helium," from the Greek *helios*, the Sun. Helium was finally discovered on Earth in 1895 by William Ramsay, as a remnant of the radioactive decay of uranium in the mineral Norwegian cleveite. Helium was soon found to be present in substantial quantities in gas wells in the United States.

A race began to liquefy helium at various laboratories, and in 1908 Heike Kamerlingh Onnes won that race at the University of Leiden, the Netherlands, observing that

Superfluidity and superconductivity have strong analogies to each other. Why then did over a quarter of a century pass between the discoveries of these two phenomena?

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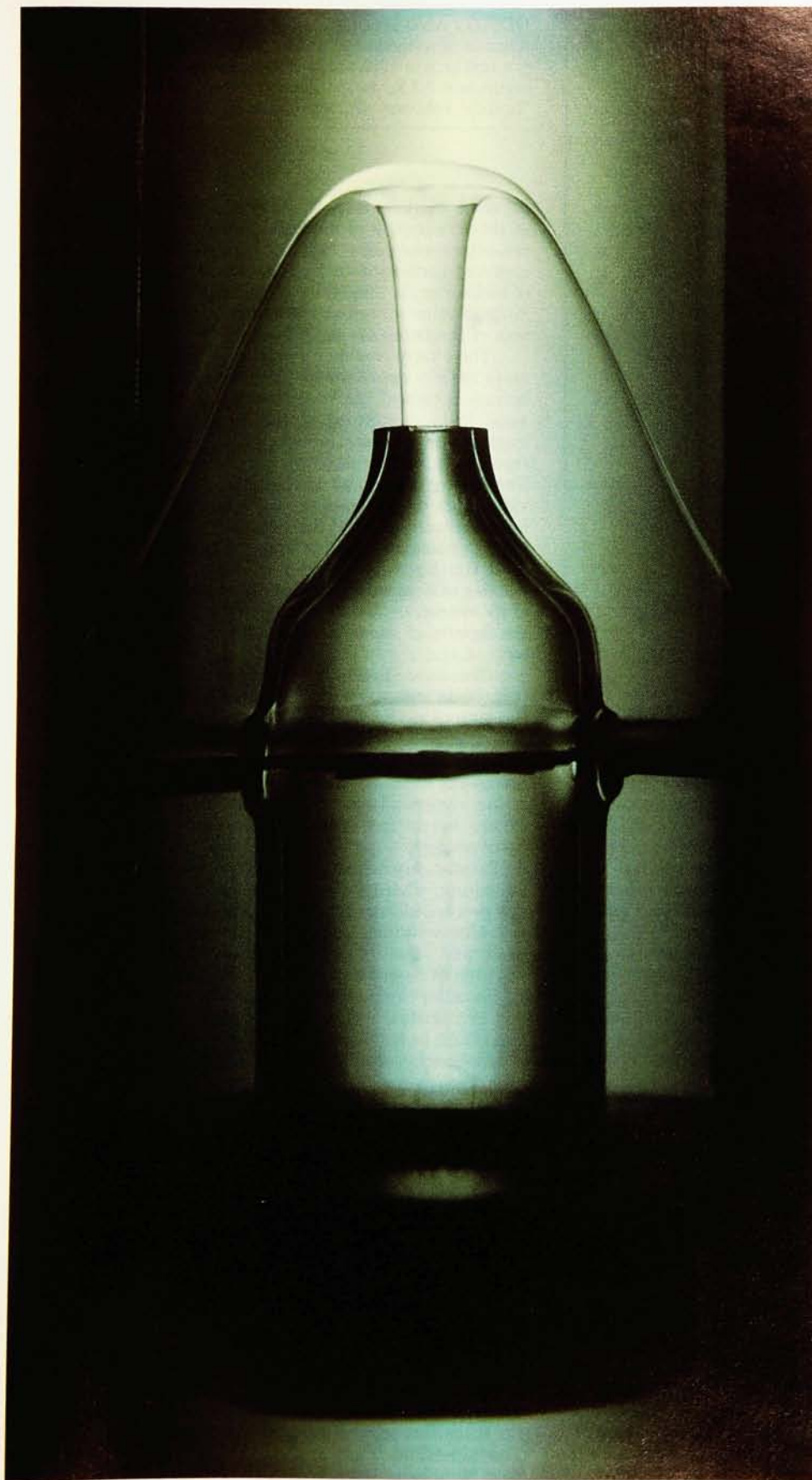
the normal boiling point was near 4 K. Onnes's team immediately tried to solidify the liquid by the usual cooling method of reducing the vapor pressure, and hence the temperature of the liquid, by pumping. By 1910 it was clear that the liquid would not freeze even at 1 K. We know today that helium at ambient pressure will remain liquid even to absolute zero, because of its large zero-point energy. The small mass of the ⁴He atom results in this large zero-point energy, which keeps the fluid's density small even though interatomic forces are strong enough to form a liquid phase at low temperatures.

In the late fall of 1910 Onnes began a series of measurements with Cornelius Dorsman and Gilles Holst that revealed, among other things, that liquid helium reaches a maximum density near 2.2 K. (See figure 2a.) This result puzzled Onnes, who found it strange that such a simple liquid should exhibit a density maximum at a seemingly uninteresting temperature. We know now that they were observing a further fundamental phenomenon, the lambda transition, that would not be recognized for many years.

The main thrust of research of the Onnes group, however, was to measure the electrical resistance of metals. They reported to the Royal Academy of Amsterdam on 21 April 1911 that they observed resistance of a thread of mercury vanishing very rapidly as the temperature dropped. Indeed, within a few months, the disappearance of resistance in mercury had been established. By March 1913 Onnes was referring in print to "the superconductivity of mercury," thus naming the phenomenon. On 10 December 1913 he received the Nobel Prize "for his investigations on the properties of substances at low temperature, which investigations, among other things, have led to the liquefaction of helium." Not long thereafter the outbreak of World War I put a temporary end to experiments with liquid helium.³

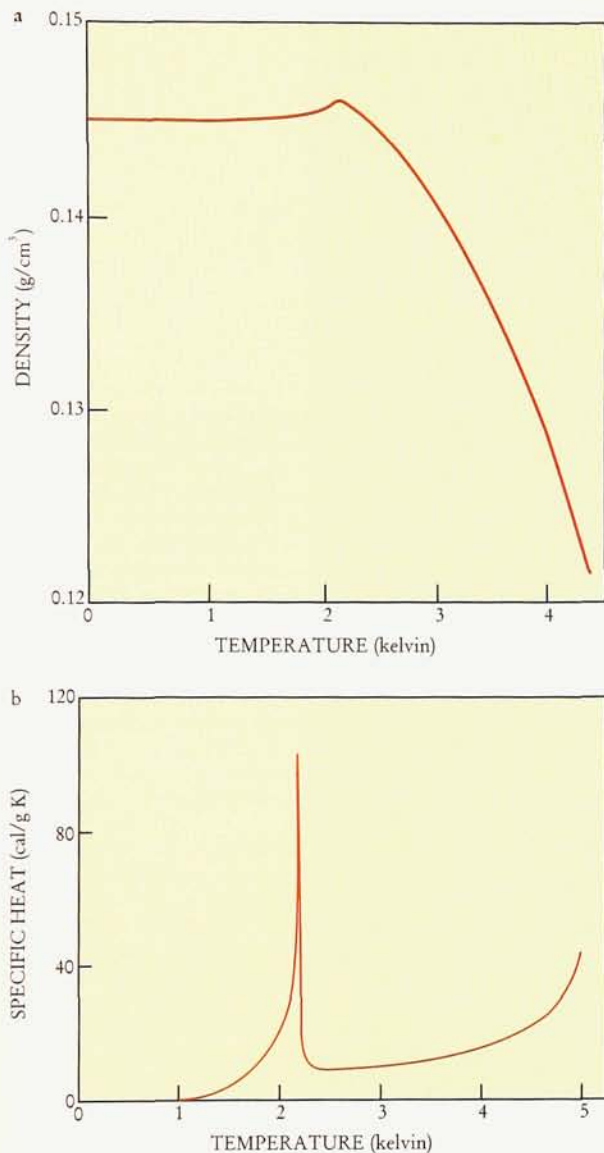
The next developments occurred in 1922 and 1923 when Onnes and Johan D. A. Boks remeasured the density maximum first observed in 1910, and Leo Dana and Onnes measured the latent heat and specific heat of liquid helium. Dana and Onnes remarked about the latent-heat curve at 2.2 K that "near the maximum density something happens to the helium which within a small temperature range is perhaps even discontinuous." This appears to be the first time that what is now called the lambda transition was identified as a discontinuity.⁴ (See my article on Dana in *PHYSICS TODAY*, April 1987, page 38.) The lambda transition is so named because the shape of the specific-heat

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HELIUM FOUNTAIN
photographed in the 1970s
by Jack Allen at the
University of St. Andrews,
in Scotland. Allen, one of
the discoverers of
superfluidity, was the first
to observe this spectacular
phenomenon. **FIGURE 1**

DENSITY AND SPECIFIC HEAT of liquid helium as a function of temperature. a: The peculiar density maximum was first seen in 1910 and suggested that something important occurs near 2.2 K. b: Specific heat shows its characteristic "lambda" behavior. (Adapted from ref. 3.) FIGURE 2



curve resembles the Greek letter λ (see figure 2b); its temperature is usually denoted by T_λ .

Two phases

An important step in the sequence of discovery was taken in 1927. In a paper entitled "Two Different Liquid States of Helium," Willem Keesom and Mieczyslaw Wolfke concluded that above the lambda transition a phase they named liquid helium I exists, and below the transition there exists a stable phase called liquid helium II, exhibiting different physical properties.³

A dramatic example of the different properties occurs during cooldown. When liquid helium is put in a cryostat and the cryostat is evacuated with a vacuum pump, the liquid begins to evaporate and cools the remaining liquid. In this way the temperature can be lowered to about 1 K. During this "pump down" the liquid boils vigorously until the lambda transition, at which it suddenly becomes absolutely quiet and bubble-free. This happens because of helium II's enormous effective thermal conductivity, owing to its two-fluid nature (which I shall discuss below). This dramatic behavior was not even mentioned in print

for some 25 years after the first liquefaction. Indeed, one of the discoverers of superfluidity, John F. (Jack) Allen, recently remarked: "In my PhD work in Toronto on superconductivity I had often seen the sudden cessation of boiling at the lambda temperature T_λ , but had paid it no particular attention. It never occurred to me that it was of fundamental significance."⁵

The slowly evolving discovery of superfluidity can be more readily appreciated if we describe how we think of helium II today.⁶ At low velocities of flow helium II acts as if it is a mixture of two fluids. One, called the superfluid, has no viscosity or entropy and can flow through extremely narrow channels without dissipation. The other, called the normal fluid, does have a finite viscosity η and carries all the entropy. We picture the liquid to be all normal fluid at the lambda transition and all superfluid at absolute zero. The proportions of each fluid can be measured, for example, by measuring the fraction of liquid that clings to an oscillating disk by virtue of its viscosity. The density of normal fluid is denoted ρ_n ; the density of superfluid, ρ_s . The total density ρ is given by $\rho_n + \rho_s$.

The superfluid is pictured as a "background fluid" that is, in effect, at absolute zero. The normal fluid is the sum of elementary excitations, or quasiparticles, consisting of phonons and rotons, which are excited from the superfluid in increasing numbers as the temperature is increased from absolute zero. Phonons are quantized sound waves and occur in solids as well as in liquid helium. Rotons are higher-energy excitations than phonons, and their properties are still under study. These elementary excitations are often investigated by inelastic neutron scattering, where a neutron excites a phonon or roton in the process of interacting with the fluid.

The two-fluid model of helium II is now highly developed, and equations of motion have been advanced that are able to describe many phenomena observed in helium II, including hydrodynamic instability and turbulence.

Physicists consider the most fundamental aspect of a superfluid to be the condensate.¹ At absolute zero some of the atoms (about 10%) are in a state of zero energy and momentum. The condensate is described by a quantum mechanical wavefunction that extends over not just individual atoms but the entire container. This macroscopic quantization of the condensate has very important ramifications. For example, if the container is rotated slowly, the normal fluid will move with the container, but the superfluid will remain at rest. Above some critical velocity of rotation,⁷ one quantized vortex line will appear in the center of the container, and every atom in the container will have an angular momentum \hbar . This results in a lockstep motion of the superfluid.¹

In superconductivity, a dramatic demonstration of frictionless flow is the perpetual flow of electricity round a superconducting ring. One can establish a persistent current in the ring by applying a magnetic field through the loop above the transition temperature, cooling through the transition temperature and removing the applied field. The superfluid fraction of helium II also can be made to flow in a loop, usually a tube packed with fine emery

powder to prevent the normal component from moving. One starts the flow by rotating the loop above the lambda transition, then cooling it through the lambda transition and stopping the rotation. The presence of the supercurrent can be detected by the fact that the superfluid flow in the loop acts like a fluid gyroscope and has a gyroscopic reaction when the axis of rotation is disturbed.

A famous lecture demonstration

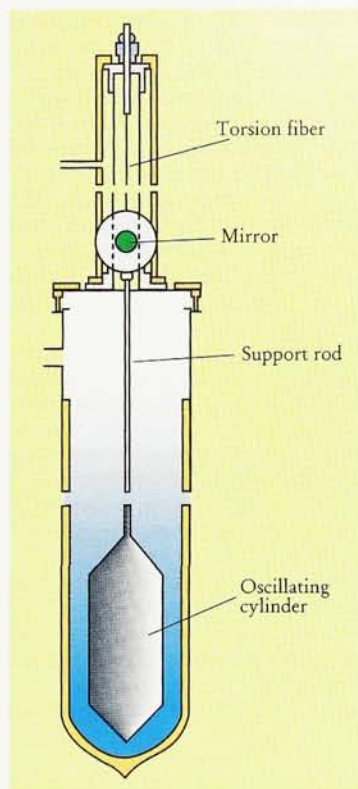
At the end of the 1920s the story of the discovery of superfluidity switches from Holland to Canada. Allen was born in 1908 in Winnipeg, Manitoba, Canada, and studied physics at the University of Manitoba, where his father was the first professor of physics. In 1929 Allen went to the University of Toronto and began to work under the supervision of Sir John McLennan, who had built a copy of Onnes's helium liquefier in 1923. Much of Allen's thesis research concerned superconductivity, and early in 1932 he designed and built a cryostat to study persistent currents in superconducting rings.

This cryostat was the source of a famous event in low-temperature physics.² McLennan was asked to give an evening discourse on superconductivity at the Royal Institution in London in 1932. Deciding that a demonstration would enliven the lecture, McLennan took Allen's cryostat to England. Because the closest source of liquid helium was in Leiden, across the North Sea, McLennan asked his friend William Francis-Sempill, Lord McMaster of Sempill (a Scottish estate) to fly the cryostat to Leiden to be filled, to start the superconducting current in the lead ring and to return to London. Sempill was a prominent and colorful aviator and a vigorous promoter of aeronautical affairs generally.

The cryostat was filled in Leiden at about 3 pm the day the demonstration was to take place, and Keesom and Gerrit Jan Flim, Leiden's chief technician, drove to Schiphol airport near Amsterdam to meet Sempill, who had arrived in a single-engine airplane. Flim boarded the airplane and carried the cryostat in his hands during the flight. The trip was rough and a good deal of the liquid evaporated. They landed at Lympne airfield in England, passed their strange load through customs and proceeded to Hanworth airfield near London. A fast taxi ride got them to the Royal Institution by 8:30 pm, and the cryostat was deposited before McLennan and his audience. The magnetic field produced by some 200 amperes circulating in the superconducting ring was demonstrated by means of a compass fitted with a mirror to reflect light on a screen. After the lecture the cryostat was emptied and the audience shown that it contained only a lead ring. Today this cryostat is in a museum at the Royal Institution.

Misener and Kapitsa

In 1935 Donald Misener, another graduate student at the University of Toronto, performed a novel experiment to determine the viscosity of helium II. Writing to me in 1988, Misener explained that he embarked on this venture because had to do some research as a requirement for the MA degree in science: "It was evident that the physical properties of this liquid had never been measured even



VISCOSITY MEASUREMENT SCHEME used by Donald Misener in 1935. An oscillating pendulum immersed in liquid helium measures the liquid's viscosity. The suspended cylinder is 2.5 cm in diameter and 9 cm long; the entire apparatus is about 1 meter in height. The cylinder's conical ends keep impurities from entering it and deflect the bubbles that occur in helium I. (Adapted from ref. 8.) **FIGURE 3**

though it showed some peculiar behavior patterns (little buckets of it emptied themselves by the liquid climbing up the sides and dropping off the outside—and if a flask of the stuff was jarred the liquid kept sloshing with very little damping)."

Misener constructed a pendulum consisting of a cylinder suspended in liquid helium by a torsion fiber and set in rotary oscillations. (See figure 3.) The unusually long decay time for these oscillations showed that the viscosity was small indeed—an order of magnitude less than that of air—and that it all but disappeared at the lambda transition.⁸ We know today that the viscosity of helium II does not disappear at the lambda transition, but that Misener's oscillating apparatus was measuring damping depending on $\eta\rho_n$ and not the viscosity η alone, which varies slowly as the temperature is lowered. The density ρ_n of normal fluid, however, drops very rapidly as the temperature is reduced below the lambda transition.

Another central figure in the discovery of superfluidity was the Russian physicist Peter Leonidovich Kapitsa, who was born in Kronstadt in 1894, the son of a general in the Czar's engineer corps. He was educated at the Polytechnic Institute of nearby Saint Petersburg as an electrical engineer, graduating in 1918. He remained there as a lecturer until 1921, during which time he came to know Abram Ioffe, an outstanding Russian physicist and a student of Wilhelm Röntgen, the discoverer of x rays. Just as Kapitsa was becoming interested in physics, an influenza epidemic carried off his wife and two children. This tragedy, and the unstable situation following the revolution, convinced Kapitsa to make his way eventually to Cambridge, England where he became a student of Ernest Rutherford's in the Cavendish Laboratory. Initially he studied radioactivity, but his engineering background soon took his interests to the generation of large magnetic fields. In 1925 he was elected a fellow of Trinity College.

By 1928 Kapitsa was heading a department of magnetic research and had begun to realize that he should be examining materials at very high magnetic fields and very low temperatures. A liquid hydrogen plant was constructed to make this possible. Rutherford, as president of the Royal Society of London, appointed Kapitsa Messel Professor of the Royal Society in 1930 and established a new laboratory for research at high fields and low temperatures called the Royal Society Mond Laboratory. In 1929 Kapitsa was elected a fellow of the Royal Society and a corresponding member of the Academy of Sciences of the USSR. Indeed, Kapitsa maintained his citizenship, and beginning in 1926 paid visits to Moscow almost every year.

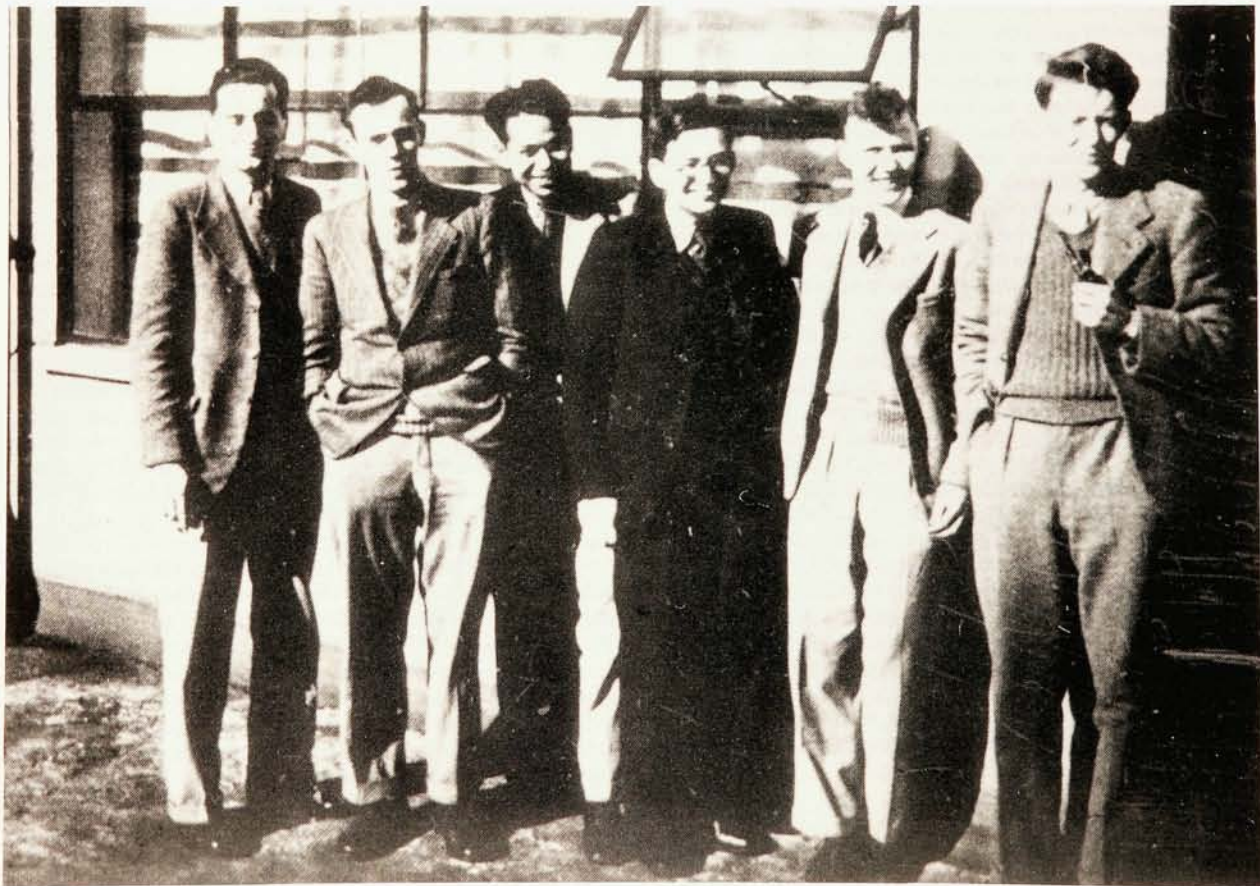
Seeing the need for temperatures even lower than those attainable with liquid hydrogen, Kapitsa again used his superb skills as an engineer and by 1934 had successfully constructed a helium liquefier of his own unique design at the Mond Laboratory. This liquefier was the forerunner of the modern machines in use today, and a version of it built at Yale University by Cecil T. Lane just after World War II was in the laboratory at Yale when I came as a graduate student in 1952.

Allen (pictured on the right in figure 4) arrived in Cambridge in the autumn of 1935 hoping to work under Kapitsa, but Kapitsa was being detained by Stalin in Russia, having gone back as usual in the early summer expecting to return to Cambridge in the autumn. The reasons for Kapitsa's detention will perhaps never be

completely clear, but the historian Lawrence Badash has suggested that one reason may have been the Soviet government's hope that Kapitsa could be instrumental in the electrification of the nation.⁹ Production of energy was to be a first step in the restructuring of the Soviet economy after the revolution. When it became clear that Kapitsa could not return, Cambridge allowed the Soviet Union to buy the entire equipment and contents of the Mond except for the helium liquefier. Kapitsa soon had a liquefier built in Moscow and quickly established himself at home as a major figure in physics.

Viscosity measurements

The 8 January 1938 issue of *Nature* carried two letters on a different type of viscosity measurement in helium II: flow through a channel or tube. "Viscosity of Liquid Helium Below the λ Point" was by Kapitsa in Moscow,¹⁰ and "Flow of Liquid Helium II" was by Allen and his graduate student Misener in Cambridge.¹¹ The two papers exploited essentially the same idea—to determine the viscosity by flow through channels instead of by oscillating cylinders. In both experiments pressure differences were measured by means of liquid levels, which, owing to the low density of liquid helium, correspond to small pressure differences. Kapitsa used the apparatus shown schematically in figure 5. When the tube filled with liquid helium II was raised, the liquid quickly flowed out, at a rate that suggested a maximum viscosity of 10^{-9} poise—indeed so



ALLEN and some associates on the roof of the Mond Laboratory, in Cambridge, England, in 1936–37. Left to right: a visitor named Hirschlaff, graduate students Teddy Shire and Zaka Uddin, theorist Rudolf Peierls, a graduate student named Curtis and Allen. Allen, Peierls and Uddin showed in 1937 that the heat conductivity of helium II becomes essentially infinite in very fine tubes. FIGURE 4

small that Kaptisa guessed by analogy to superconductors that it might be zero and "that the helium below the λ -point enters a special state that might be called a 'superfluid.'"¹⁰

Allen and Misener measured the flow through narrow tubes of radii 10^{-5} – 10^{-2} cm. They found that in the narrowest tubes the flow is almost independent of pressure and observed that "consequently any known formula cannot, from our data, give a value of viscosity which would have any meaning."¹¹

These two letters to the editor mark the discovery of superfluidity—or, more precisely, the realization that helium II exhibits superfluidity. Much more, however, remained to be done, for the oscillating cylinder and flow through channels turned out not to be measuring the same thing. In the two-fluid picture, the oscillating cylinder is damped by the normal fluid, whereas it is the superfluid that passes through the narrowest tubes without friction. Kapitsa mentioned the Toronto viscosity measurements⁸ and concluded (erroneously) that the reported finite viscosity must be due to turbulent flow.

Fountain effect

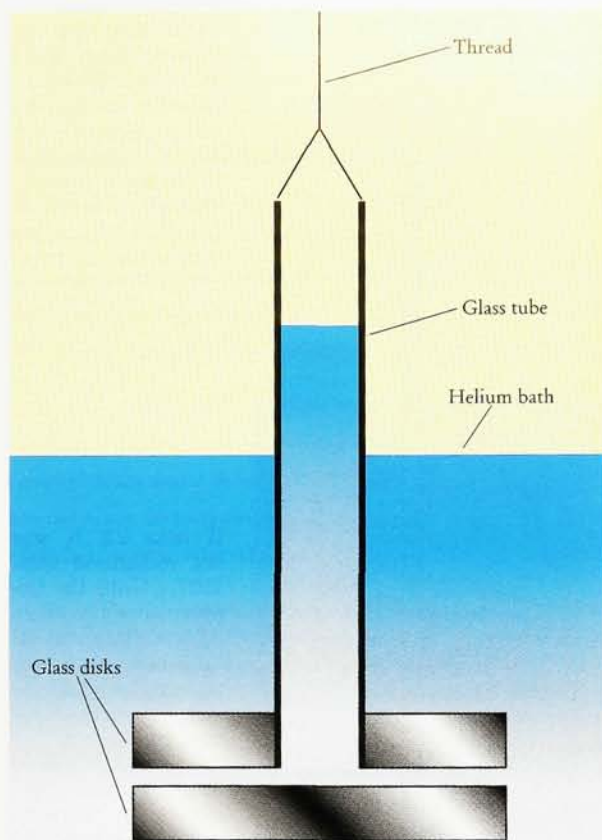
Shortly afterward, Allen and Harry Jones discovered the thermomechanical effect in helium II, popularly known as the "fountain effect."¹² This was an accidental discovery made in the process of investigating thermal conduction in fine tubes. Allen, in a recent account⁵ and in letters to me, wrote that in the experiments the conductivity of heat appeared to increase as the size of the capillary bore carrying the heat became smaller. For the smallest tubes and lowest temperatures, the rise in liquid level shown in figure 6 was observed for the first time. Allen recalls:

In addition, in the same dewar, was a small tube with an open bulb at the bottom containing emery powder, since we thought we would examine the flow through powder to compare it with the flow through a smooth tube. To make sure that the right piece of apparatus appeared in the clear strip I had a small pocket torch [flashlight]. As the emery powder tube came into view in the light of the torch helium spurted out of the top of the tube. It continued to spurt as long as the torch light shone on the powder and ceased when a card cut off the light, and therefore the radiant heat, to the bulb. The fountain had appeared. Admittedly it was only one or two millimeters high, but it was there. Great excitement, everybody in the lab was brought in to see it, and a camera rigged to take a picture.

By the next week we had a properly designed tube to produce a real fountain about 15 cm high when irradiated by a 60 watt desk lamp bulb.

Figure 6 depicts the improved fountain apparatus, and figure 1 is a modern photograph of a beautiful helium fountain. The black horizontal line in the photo is the electrical heater connection; the heater is a spiral inside the glass apparatus.

The two-fluid picture described earlier was first put into mathematical form by Laszlo Tisza around 1938–40.¹³ These equations showed that sound in helium II consists of ordinary (first) sound, which is fluctuations in total density, and second sound, which is fluctuations in the densities of the normal and superfluid components.⁶ Second sound makes itself known as temperature fluctuations and can be generated by heaters and detected by thermometers. The entry of Lev Landau into the field in 1941 brought a more rigorous treatment of the two-fluid equations; this effort was helped by the existence of new



CHANNEL-FLOW SCHEME by Peter Kapitsa in Moscow to measure the viscosity of helium II. Kapitsa raised the optically flat glass disks and glass tube from the helium bath by means of the thread. The viscosity was measured by the pressure drop when the liquid flowed through the narrow gap between the disks. The pressure difference was given by the height of the liquid column in the glass tube. Above the lambda transition temperature T_λ a level difference could be observed for several minutes. Below T_λ the difference disappeared in seconds, leading Kapitsa to conclude that the viscosity of helium II was at least 1500 times less than that of helium I. FIGURE 6

experiments and by the development of the quasiparticle picture of the normal component mentioned above.

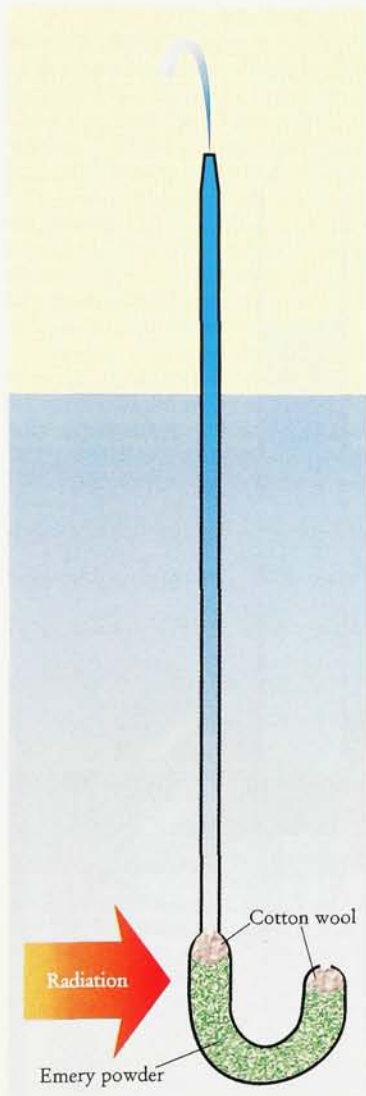
Reasons for slow discovery

Perhaps now we can speculate as to why superconductivity was discovered in 1911, only three years after the first liquefaction of helium, and superfluidity in 1938, 30 years after the liquefaction.

First, there was already much experimental and theoretical interest in the fall with temperature of electrical resistance in wires. This decrease was already seen with liquid air and liquid hydrogen. But no past experience even remotely resembling superfluidity was available before the liquefaction of helium.

Second, once superconductivity was discovered it was immediately obvious to Onnes and others that there were important applications, such as persistent-current magnets, to be developed. Superconductivity was soon found in other materials, thus widening the accessibility of and interest in the phenomenon.

Third, the subtle transformation from helium I to helium



SETUP USED BY ALLEN in the discovery of the fountain effect. The powder, called a superleak, forms many fine channels for superfluid flow. When radiation warms the powder, quasiparticles (rotons and photons) are excited from the superfluid and expand. The expansion pushes up on the free surface of the liquid, drawing superfluid from the bath through the superleak. The pressure becomes so high that fluid exits the top of the tube continuously as long as the powder is warmed. FIGURE 6

II near 2.2 K was not recognized until 1927. Until the importance of the lambda transition was established there was no real motivation to look for other exotic phenomena.

Fourth, the early viscosity measurements in Toronto showed a substantial drop in the damping of the oscillating cylinder below the lambda transition but not the disappearance of friction. The disappearance of friction had to wait for the 1938 experiments, which showed the analogy between supercon-

ductivity and superfluidity: Electrons flow through a superconducting wire with no voltage difference, and a superfluid flows through narrow channels with no pressure difference. The possibility of turbulent flow leading to false conclusions about the viscosity was fully appreciated by all investigators.

Finally, there was no great scientific leader active in understanding liquid helium in the early days. When Kapitsa and the great theoretical physicist Landau, followed by physicists such as Fritz London, Lars Onsager, Richard Feynman and other greats, came on board, there was a tremendous surge of excitement, which lasted for many years and helped bring the subject to its present state of understanding.

As we have noted, the forced retention of Kapitsa by Stalin in 1934 resulted in the founding of a new low-temperature laboratory in Moscow. By 1941 the work there had established one of the most important chapters in the history of Russian (and indeed all) physics. Kapitsa not only began experimental work in Moscow, but he was in close contact with Landau and his graduate students. Landau, with his colleague Evgenii Lifshitz, wrote the magnificent *Course of Theoretical Physics*, a ten-volume series that has had a major impact on all of modern

physics. The nature of superfluidity was rapidly established in Moscow and elsewhere and was eventually recognized by the award of Nobel Prizes to both Kapitsa and Landau. It is somewhat surprising that the Mond Laboratory, which produced many distinguished low-temperature investigators over the years, seems to have received less credit than it truly deserves.

The importance of superfluidity lies mainly in what it tells us about the condensed state of matter. In particular, the quantum mechanical consequences of the existence of a condensate lie at the very foundation of our understanding of the behavior of matter at low temperatures. The lambda transition in helium has proved to be a major testing ground for models of phase transitions, which are of far broader significance than the lambda transition by itself. The two-fluid model has proved to be a major testing ground for understanding a new system of hydrodynamic equations. Superfluidity is becoming conceptually well understood and offers an entirely new frontier in fluid mechanics for the study of inviscid flows, stability, turbulence and shock waves.

The tendency for helium II to become turbulent very easily because of its low viscosity was understood by the pioneers in this subject. This tendency may itself evolve into a tool for the generation of the highest-Reynolds-number flows ever achieved under laboratory conditions. Such work is now a major thrust of low-temperature physics.

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