Marc Macias-Fauria is at the School of Geography and the Environment, University of Oxford, Oxford OX1 3QY, UK.

e-mail: marc.maciasfauria@ouce.ox.ac.uk

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In Retrospect

Eighty years of superfluidity

In 1938, two studies demonstrated that liquid helium-4 flows without friction or viscosity at temperatures close to absolute zero. The finding led to major advances in our understanding of low-temperature physics.

WILLIAM P. HALPERIN

In the early twentieth century, scientists discovered the non-intuitive phenomena of superconductivity and superfluidity, in which electrons and atoms, respectively, flow without resistance over great distances. Superfluidity was beautifully demonstrated 80 years ago in two papers published in *Nature* by Allen and Misener¹ and Kapitza². The authors observed the flow of liquid helium-4 through extremely narrow channels and showed that the substance becomes a superfluid at very low temperatures. The studies presaged the firm understanding of the relationship between superfluidity and superconductivity that now exists, and which provides the foundation for investigating unconventional superconductors and superfluid phases.

Allen and Misener observed the flow of liquid helium-4 through long, thin tubes, and found that the fluid's viscosity became immeasurably low at temperatures below 2.17 kelvin. Kapitza obtained similar results by measuring the flow through a small gap between two glass disks (Fig. 1). With foresight, Kapitza noted a possible connection to superconductivity, for which a complete theory was eventually realized³ in 1957 by Bardeen, Cooper and Schrieffer (BCS). Shortly after the two *Nature* papers were published, an explanation for the superfluidity of liquid helium-4 was offered: Bose–Einstein condensation⁴, the process whereby many particles known as bosons ‘condense’ into a single quantum state.

In the quantum world, particles of the same type are indistinguishable, and there are only two classes of particle: fermions and bosons. However, an even number of interacting fermions can make a composite boson — for example, an atom of helium-4 is a composite boson that comprises six fermions (two protons, two neutrons and two electrons). At sufficiently low temperatures, helium-4

atoms undergo Bose–Einstein condensation and become a superfluid. Similarly, in the BCS theory of superconductivity, electrons that have a suitably attractive interaction can combine into charged composite bosons called Cooper pairs, which condense to form a superconductor.

In the wake of the Second World War, substantial quantities of the light isotope of helium, helium-3, became available through production of the heavy isotope of hydrogen (hydrogen-3 or tritium) for use in the hydrogen bomb. Because helium-3 contains an odd number of fermions (two protons, one neutron and two electrons), it is not a composite boson. It might therefore be considered that Bose–Einstein condensation could not take place and that helium-3 could never be a superfluid. However, the success of the BCS theory suggested another possibility: composite bosons comprising Cooper pairs of helium-3 atoms might condense into a superfluid, much like the electrons of a BCS superconductor.

The properties of this hypothetical superfluid were studied theoretically^{5–7} in the 1960s. Research on the subject then exploded following the unexpected discovery⁸ in 1972 of this superfluid at temperatures below 0.003 K. At first, the observations were interpreted as spontaneous nuclear magnetic ordering in solid helium-3, but shortly afterwards, they were correctly identified as the transition to a superfluid⁹. Nuclear magnetic ordering in solid helium-3 was discovered¹⁰ two years later at a temperature of 0.001 K.

Cooper pairs have two types of angular momentum, characterized by the orbital quantum number (L) and the spin quantum number (S). Conventional BCS superconductors have $L = 0$ and $S = 0$, whereas superfluid helium-3 has $L = 1$ and $S = 1$. Nevertheless, the superfluid's properties can be understood using a modified version of the BCS theory¹¹. The discovery of superfluid helium-3

50 Years Ago

There was an increase in the number of patients discharged from British hospitals in 1964, and a decrease in the average length of stay in hospital compared with 1962 and 1963. Men and boys stayed in hospital an average length of 18.3 days in 1964; women and girls ... averaged just under two days less (16.7 days) ... These are some of the findings in ... the *Report on Hospital In-Patient Enquiry* for the year 1964 ... The report contains detailed tables prepared from the 1964 ten per cent sample of discharges and deaths recorded ... The tables are a mine of information ... Injuries, poisonings and the like are all analysed in great detail according to whether they were caused by road traffic accidents, accidents in the home, or “other” mishaps.

From *Nature* 27 January 1968

100 Years Ago

It was stated officially ... that the Admiralty had tested many methods of disguising mercantile shipping. One of these methods is to paint the ship with various quaint combinations of different colours. But this does not appear to have proved much of a success ... Mr. Abbott H. Thayer ... was one of the first to recognise that a high degree of invisibility is conferred on certain birds by the simple adaptation of being dark above and whitish below. He took two wooden decoy ducks, and placed them against a sandbank. One was coloured like the sand ... the other was coloured on its upper parts darker than the surrounding sand, and graded below to pure white. At a short distance the first was still clearly visible, but the second was quite lost against its background ... Some modification of this experiment has been tried on ships ... but this device has not proved so successful as had been hoped.

From *Nature* 24 January 1918

Figure 1 | Experimental evidence for superfluidity. In 1938, Allen and Misener¹ and Kapitza² showed that liquid helium-4 becomes a superfluid — a fluid with zero viscosity — at very low temperatures. Whereas Allen and Misener measured the flow of liquid helium-4 through long, thin tubes, Kapitza observed the flow (red arrows) from a glass tube to a helium bath, through a narrow gap between two glass disks. The separation between the disks was adjusted using a thread such that the level of the column of liquid in the glass tube was above the level of the helium bath. At temperatures above 2.17 kelvin, Kapitza found that the difference in height between these levels was maintained for several minutes. Conversely, at lower temperatures, the difference disappeared in seconds. Kapitza concluded that the viscosity of liquid helium-4 must be immeasurably low below 2.17 K. (Figure adapted from ref. 2.)

therefore marked the birth of unconventional superconductivity — and, more precisely, of superfluids that break certain fundamental symmetries of the normal (non-superfluid) state. The non-zero values of L and S in superfluid helium-3 correspond to broken rotational and time-reversal symmetries, which cause the substance to have a non-trivial topology.

In the absence of a magnetic field, superfluid helium-3 has two phases: A and B, with the B phase dominating the pressure–temperature phase diagram (a graph that plots the physical state of a material at various pressures and temperatures). The B phase can exist in many excited states, as a consequence of broken rotational symmetry associated with the total angular momentum of Cooper pairs^{7,12,13}. The states of the B phase are classified by total angular momentum quantum numbers (J) of 0, 1 and 2. The $J=2$ state comprises bosons that are analogous to the famous Higgs boson¹⁴. A remarkable finding is that the broken symmetry of the B phase, and its $J=2$ state, enable the propagation of transverse sound waves^{15,16} — a feature that was unheard of in liquids and was often assumed to be a property only of rigid solids.

Since the discovery of superfluid helium-3, many unconventional superconductors have been found. The best known are copper oxide compounds known as cuprates, which have the quantum numbers $L=2$ and $S=0$, and certain heavy fermion compounds¹⁷. However, only one superconducting compound, the uranium–platinum system UPt₃, has been

discovered that has more than one superfluid phase, like helium-3. UPt₃ has $L=3$ and $S=1$, as predicted¹⁸, and one of its phases breaks time-reversal symmetry in a similar way¹⁹ to the A phase of helium-3.

In the past few years, helium-3 has been shown to exhibit new superfluid phases when confined to low-density materials called aerogels, small pores and narrow slabs²⁰. Such phases are being investigated further. Eighty

years after the discovery of superfluidity in liquid helium-4, the search is on for other scientifically interesting superfluids and superconducting materials. ■

William P. Halperin is in the Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA. e-mail: w-halperin@northwestern.edu

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BIOTECHNOLOGY

Kiss-and-tell way to track cell contacts

Transient cellular contacts are essential for the generation of an immune response, but these are difficult to measure *in vivo*. A labelling technique now offers a way to record such interactions between cells. SEE LETTER P.496

AARON P. ESSER-KAHN

Contact between two cells is a key step in the transfer of information during biological processes. However, monitoring dynamic cellular interactions *in vivo* poses many technical challenges. On page 496, Pasqual *et al.*¹ report the development of a technique that can track interactions between

cells that contact each other through receptor–ligand binding.

A key step in the development of an immune response involves contact between an antigen-presenting cell (APC), such as a dendritic cell, and an immune cell called a T cell. On the APC surface, a receptor called the major histocompatibility complex (MHC) displays a protein fragment known as an antigen. If the