New light on the intriguing history of superfluidity in liquid ^{4}He

2009 J. Phys.: Condens. Matter 21 164220

(http://iopscience.iop.org/0953-8984/21/16/164220)

IOP PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **21** (2009) 164220 (9pp) doi:10.1088/0953-8984/21/16/164220

New light on the intriguing history of superfluidity in liquid ^{4}He

Allan Griffin

Department of Physics, University of Toronto, Toronto, ON, M5S 1A7, Canada

E-mail: griffin@physics.utoronto.ca

Received 22 January 2009
Published 31 March 2009
Online at stacks.iop.org/JPhysCM/21/164220

Abstract
Surprisingly, it was 30 years after the first liquefaction of ^{4}He in 1908 that the discovery that liquid ^{4}He is not just a ‘cold’ liquid was made. Below $T = 2.18$ K, it is a ‘quantum’ liquid which exhibits spectacular macroscopic quantum behaviour that can be seen with the naked eye. Since the observation of superfluidity in liquid ^{4}He is one of the greatest discoveries in modern physics, we present a day-to-day chronology of the tangled events which preceded the seminal discovery of zero viscosity in 1938 by Kapitza in Moscow and by Allen and Misener in Cambridge. On the theory side, London argued in 1938 that the microscopic basis for this new superfluid phase was the forgotten phenomenon of Bose–Einstein condensation (BEC) first suggested by Einstein in 1925. In 1941, Landau developed a very successful theory of superfluid ^{4}He, but it was not anchored in a microscopic theory of interacting atoms. It took another 20 years for theorists to unify the two seemingly different theories of Landau and London. Experiments on trapped superfluid atomic gases since 1995 have shone new light on superfluid ^{4}He. In the mid-1930s, London had emphasized that superconductivity in metals and superfluidity in liquid ^{4}He were similar. Experiments on trapped two-component Fermi gases in the last five years have shown that a Bose condensate is indeed the basis of both of these superfluid phases. This confirms the now famous Bardeen–Cooper–Schrieffer–BEC crossover scenario developed for superfluidity by Leggett and Nozières in the early 1980s but largely ignored until a few years ago. The study of superfluid ^{4}He will increasingly overlap with strongly interacting dilute quantum gases, perhaps opening up a new era of research on this most amazing liquid.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The liquefaction of helium was achieved by Heike Kamerlingh Onnes at Leiden University on 10 July, 1908 [1]. His long and careful preparation has been compared to the energy and planning needed to climb Mt Everest. In the process, Onnes set up the first big-science laboratory within a university environment, with a team of graduate students and technical assistants.

The unexpected discovery of superconductivity in metals by Onnes in 1911 diverted attention from the remarkable properties of liquid helium and relegated it to being mainly used as a coolant for almost two decades. The first strong evidence that there was an additional phase transition in liquid helium at 2.18 K was obtained in 1928. That it was a ‘superfluid’ below this temperature was only discovered in 1938.

This paper covers two main topics. We first revisit the history of the dramatic discovery in 1938 of superfluidity in liquid helium (see also [2, 3]). We then describe some of the key steps in understanding the microscopic origins of superfluidity over the next 70 years. In this historical article, I will not discuss the physics of superfluidity (see for example, [4, 5]).

2. Liquid helium in Leiden before 1934

Towards the end of the 19th century, there was a race to liquefy the permanent gases in the quest for lower and lower temperatures [1]. Oxygen was liquefied in 1893. Liquid Hydrogen was produced in 1898 by James Dewar in London. This was thought to be the lowest temperature liquid, until calculations based on the law of corresponding states (based on

0953-8984/09/164220+09$30.00

the van der Waals equation of state) showed that liquid helium would have a lower boiling temperature. Helium, first detected in the sun (hence helios) in 1868, was collected as a gas by Ramsey in 1895. On earth, helium atoms are produced from alpha-particle decay of radioactive nuclei, as first understood by Rutherford in 1907.

The boiling temperature of liquid ^{4}He is 4.2 K. It is a very low density, colourless liquid. After 1908, liquid ^{4}He was mainly used as a 'cold liquid' to cool metals and other solids. Onnes and his co-workers discovered superconductivity in 1911, and the study of this state of matter diverted attention from exploring the unique properties of liquid ^{4}He. It took until 1927 before it became clear from work at Leiden that there was another, much more interesting, phase transition at 2.18 K. In 1924, Onnes and coworkers had noticed that the density changed at $T = 2.18$ K, well below the boiling temperature 4.2 K (Onnes died in 1926). However, it was only in 1928 that Keesom and Wolfke [6] concluded there was a phase transition at 2.18 K and introduced the terms He I and He II for the two phases. Finally, in 1932, Keesom and Clusius [7] measured the famous peak in the specific heat (with a shape like the Greek letter lambda). However, all these results only involved measurements of thermodynamic properties. No one thought to address the hydrodynamic or flow properties of this 'new liquid phase'. Keesom had noted in 1930 that the low temperature phase (He II) seemed to flow very easily through small leaks in the apparatus [1], but mentioned this only as an experimental irritation!

3. Events leading up to the discovery of superfluidity: Toronto and Moscow

We first review research on liquid ^{4}He in Toronto in the decade 1923–1933. From 1900–1932, John McLennan was Head of the Department of Physics at the University of Toronto. He was awarded the first PhD in science in Canada in 1900, based on his research at Cambridge University in 1898–1900. With enormous energy, McLennan built up a research lab that was one of the best in North America (for more details about McLennan and Toronto, see [8]).

What was the origin of research on liquid helium at Toronto, where there was no tradition of research in low temperature physics? In 1915, during WWI, McLennan was asked by Britain to make a survey of the availability of helium gas in the British Empire. The plan was to use helium gas as a safe substitute for hydrogen gas in military airships. McLennan organized teams to do this, making a careful study of gas wells in Canada and other countries. This led to setting up several helium gas extraction and purification plants in Canada. After WWI, when ^{4}He gas was no longer of military interest, McLennan decided to use the large supply of gas at his disposal to produce liquid ^{4}He at Toronto.

In 1919, Leiden was still the only place in the world that could produce liquid ^{4}He. McLennan asked for assistance from Kamerlingh Onnes, who generously gave Toronto the detailed drawings of the Leiden liquefier and advice. The tradeoff was that McLennan arranged for Leiden to obtain a supply of helium gas, which was in short supply in Europe after WWI. Helium gas sources were controlled by the British military, with McLennan as a scientific advisor.

On 24 Jan., 1923, one litre of liquid helium was produced at U of T, the second lab in the world to do this [8, 9]. This ushered in a decade of pioneering research at Toronto on superfluid helium and superconductors. McLennan is given credit for the first explicit observation that superfluid helium is a very strange 'fluid'. In a paper published in 1932 [10] on the scattering of light, he noted that the rapid bubbling which appears just above the transition temperature T_c abruptly disappears at T_c and below. Later, it was realized that this phenomenon is a dramatic effect of the appearance of superfluidity, and may be viewed as a macroscopic quantum effect (see figure 1). Many other people had observed this same phenomenon, but they had not felt it was important enough to even mention it!

McLennan attracted many talented graduate students to work in low temperature physics. Two of these were Allen and Misener (shown in figure 2), who would later go to Cambridge University to work on liquid helium [2].

We next make some brief remarks on the life of Kapitza [12, 13]. Kapitza arrived in Cambridge in 1921 as a graduate student from the Soviet Union, to study nuclear physics with Rutherford. He was a brilliant as well as charismatic person, and became a close friend and protégé of Rutherford, the head of the Cavendish Lab. Kapitza liked technical challenges, and became very interested in the properties of metals at very low temperatures at very high magnetic fields. Rutherford used funds of the Royal Society to build the Mond Laboratory in 1933, with Kapitza as Director. Kapitza needed large amounts of liquid ^{4}He for his work, and this led him to an innovative new design for a helium liquefier. It successfully produced liquid ^{4}He in 1934.

On one of his regular family visits to the Soviet Union in September, 1934, Kapitza was put under house arrest. He was given generous funding to build a new Laboratory in Moscow. Kapitza asked Rutherford and John Cockcroft (the acting Director of the Mond Lab) for assistance. They arranged for two senior technicians to be sent to Moscow, as well as research equipment and supplies not easily available in the Soviet Union.

Allen had applied to go to Cambridge in 1934 to work with Kapitza. When Allen got there in the fall of 1935, the Mond Lab was in a somewhat chaotic state [2]. However, he soon became the de-facto head of the group working using liquid helium. In 1937, Allen *et al* [14] published a paper on the anomalous thermal conductivity of helium II in thin capillaries, which had a big impact.

The first evidence for superfluidity was, in fact, a seminal experiment in 1935 by Misener, a young graduate student working at Toronto. This involved measuring the shear viscosity of liquid helium just below the transition temperature $T_c = 2.18$ K from the decay of the torsional oscillations of a rotating cylinder. Misener found that the viscosity decreased sharply as one went just below T_c, although it was still finite. We now know that this decrease was in the normal fluid viscosity and was related to the appearance of the superfluid component below T_c, resulting in a decreased normal fluid

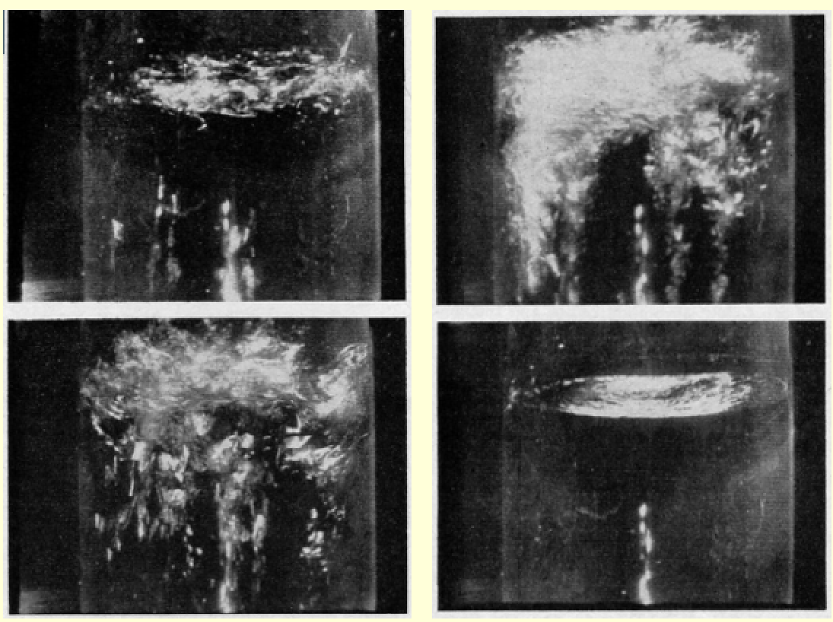

Figure 1. These pictures show the boiling as one goes from above the superfluid transition temperature to below. The dramatic cessation of boiling is a dramatic consequence of two-fluid hydrodynamics setting in below T_c (from [11]).

Figure 2. From left to right, Allen, Misener and Kapitza, all taken in the period 1937–38 (all photos by permission of the author).

density. This was the first evidence that He II was a new kind of liquid. The article [15] in the journal *Nature* reporting this was noticed by the growing low temperature community (while carried out by Misener, this work was published under the name of Burton, the head of the Toronto lab, causing some later confusion).

Misener went to Cambridge to do his PhD in the period 1936–1938. He soon started a research project with Allen, studying the viscosity of helium flowing in thin glass capillaries. As discussed in [2], on 24 Nov., 1937, they found that liquid helium below 2.18 K showed almost zero viscosity. Their work was published as a letter in *Nature* on 8 Jan., 1938 [16], following a paper by Kapitza [17] announcing the same results using a different method. These two short papers (see figure 3) marked the beginning of the study of quantum fluids, a field of research which continues today.

4. The discovery of superfluidity

Two groups independently discovered superfluidity: Allen and Misener at Cambridge University and Kapitza in Moscow (see figure 2). This discovery was quite unexpected and must be viewed as one of the seminal developments in modern physics. The details of this discovery are thus of special interest [2, 3]. While the low temperature community has generally given equal credit to Kapitza as well as Allen and Misener for the discovery, there has been a tendency in the larger world to give Kapitza the main credit. Kapitza was cowinner of the Nobel Prize in Physics in 1978 at age 84, with the independent work of Allen and Misener being completely ignored. I give the detailed chronology of events on the next page, including new information obtained from the private papers of both Allen and Misener. This chronology shows clearly that Kapitza, Allen and Misener were all very entangled with each other and that the Mond Lab at Cambridge also played a crucial role in Kapitza's research.

1937	
Feb. 22	Kapitza's new liquefier in Moscow produced liquid ^{4}He (built with help of technicians and parts sent from the Mond Lab).
Oct. 19	Rutherford dies suddenly.
Nov. 11	First viscosity experiment by Allen and Misener at the Mond Lab.
Nov. 24	Discovery of non-viscous flow by Allen and Misener.
Dec. 3	*Nature* receives the paper by Kapitza.
Dec. 10	Kapitza sends a letter to Niels Bohr telling him about his zero viscosity results and his Nature paper.
Dec. 17	W L Webster (another Canadian from Toronto and Kapitza's first Cambridge student) brings news from Moscow about Kapitza's new results and asks Cockcroft to check the page proofs.
Dec. 18	Cockcroft writes to Kapitza, saying he has just heard of of Kapitza's new data and informs him about identical results already obtained at the Mond Lab.
Dec. 21	Allen and Misener submit their paper to *Nature*, which was received the next day. Cockcroft tells the editor to send proofs to Allen's address in Cambridge.
Dec. 25	Cockcroft (away for Christmas) sends a letter to Kapitza that he has corrected the proofs and sent them back to *Nature*.

1938	
Jan. 8	Both superfluidity papers are published in *Nature*.
Jan. 12	Allen discovers the fountain effect!
April 9	Fritz London's paper on the connection between superfluid ^{4}He and BEC appears in *Nature*.
April 28	Landau arrested by the KGB and spends the next year in prison. He was released through the efforts of Kapitza, who argued that Landau was needed to develop a theory of superfluidity. Landau did in 1941!

What do we learn from all this?

(1) Allen and Misener discovered superfluid flow quite independently from Kapitza [2, 3].

(2) Kapitza's work was clearly inspired by earlier work at Toronto and at Cambridge. His paper has only three references, all to research by Misener, Allen and their coworkers [14, 15, 18].

(3) The research of both groups was tied up closely with the Royal Society Mond Laboratory, with Cockcroft playing a complicated role as an intermediary between Moscow and Cambridge.

(4) There are indications that Kapitza knew that Allen and Misener were working on the same topic and was worried that they might beat him.

(5) The sudden death of Rutherford in late 1937 removed someone who could have brought together Kapitza and Allen. Rutherford was fiercely loyal to the Cavendish and could have been expected to defend and promote the work of his young researcher Allen.

(6) The editor of *Nature* is not to blame for Allen and Misener seeing Kapitza's paper before publication. It was Kapitza that sent Cockcroft a copy.

We briefly discuss two reasons that have been traditionally suggested as to why Allen did not deserve to share the Nobel Prize with Kapitza:

(1) Allen had gone to Cambridge to work with Kapitza and also used Kapitza's liquefier in his research. This argument ignores several important facts [2, 3]:
   (a) Allen came from Toronto as a fully independent researcher and was very experienced with liquid helium.
   (b) Allen was put into a 'vacuum' at the Mond laboratory with Kapitza absent, but effectively took over the direction of the group using liquid helium for research.
   (c) The Mond Lab at Cambridge was very generous to Kapitza. As noted above, two key technicians were sent to Moscow for two years, and all kinds of cryogenic equipment was shipped there to help Kapitza get a lab going in Moscow very quickly. In contrast, Allen had to scrounge around at the Mond Lab.

(2) Kapitza's paper was received by *Nature* two weeks before the one by Allen and Misener, and the latter had seen Kapitza's results. Thus, it is argued that the Allen–Misener paper cannot be viewed as independent research. However, from Misener's handwritten log of liquid helium runs [2], we know that on 24 Nov., 1937 Allen and Misener discovered evidence for zero viscosity. This was well before they heard of Kapitza's results. Presumably Kapitza also discovered zero viscosity at about the same time, sometime in November, 1937. It would be interesting to have a more detailed chronology of Kapitza's work in Moscow in late 1937, but I have not been able to find such information.

There is some evidence that Kapitza let the Nobel Prize Committee (however indirectly) know that he would not accept the prize if it was to be shared with Allen. This gives the only reasonable explanation why it took 40 years before a Nobel prize was given for the discovery of superfluidity. This phenomenon is at the basis of much of modern condensed matter physics and is one of the most dramatic examples of quantum mechanics in the visible world. Kapitza's Nobel prize talk in 1978 is unique in that it does not say a single word about how he discovered superfluidity but instead discusses his much later work on hot plasmas. One hears stories from Russian physicists about Kapitza not wanting to share the

Letters to the Editor

The Editor does not hold himself responsible for opinions expressed by his correspondents. He cannot undertake to return, or to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. *No notice is taken of anonymous communications.*

NOTES ON POINTS IN SOME OF THIS WEEK'S LETTERS APPEAR ON P. 83.

CORRESPONDENTS ARE INVITED TO ATTACH SIMILAR SUMMARIES TO THEIR COMMUNICATIONS.

Viscosity of Liquid Helium below the λ-Point

THE abnormally high heat conductivity of helium II below the λ-point, as first observed by Keesom, suggested to me the possibility of an explanation in terms of convection currents. This explanation would require helium II to have an abnormally low viscosity; at present, the only viscosity measurements on liquid helium have been made in Toronto[1], and showed that there is a drop in viscosity below the λ-point by a factor of 3 compared with liquid helium at normal pressure, and by a factor of 8 compared with the value just above the λ-point. In these experiments, however, no check was made to ensure that the motion was laminar, and not turbulent.

The important fact that liquid helium has a specific density ρ of about 0·15, not very different from that of an ordinary fluid, while its viscosity μ is very small comparable to that of a gas, makes its kinematic viscosity $\nu=\mu/\rho$ extraordinary small. Consequently when the liquid is in motion in an ordinary viscosimeter, the Reynolds number may become very high, while in order to keep the motion laminar, especially in the method used in Toronto, namely, the damping of an oscillating cylinder, the Reynolds number must be kept very low. This requirement was not fulfilled in the Toronto experiments, and the deduced value of viscosity thus refers to turbulent motion, and consequently may be higher by any amount than the real value.

The very small kinematic viscosity of liquid helium II thus makes it difficult to measure the viscosity. In an attempt to get laminar motion the following method (shown diagramatically in the accompanying illustration) was devised. The viscosity was measured by the pressure drop when the liquid flows through the gap between the disks 1 and 2; these disks were of glass and were optically flat, the gap between them being adjustable by mica distance pieces. The upper disk, 1, was 3 cm. in diameter with a central hole of 1·5 cm. diameter, over which a glass tube (3) was fixed. Lowering and raising this plunger in the liquid helium by means of the thread (4), the level of the liquid column in the tube 3 could be set above or below the level (5) of the liquid in the surrounding Dewar flask. The amount of flow and the pressure were deduced from the difference of the two levels, which was measured by cathetometer.

The results of the measurements were rather striking. When there were no distance pieces between the disks, and the plates 1 and 2 were brought into contact (by observation of optical fringes, their separation was estimated to be about half a micron), the flow of liquid above the λ-point could be only just detected over several minutes, while below the λ-point the liquid helium flowed quite easily, and the level in the tube 3 settled down in a few seconds. From the measurements we can conclude that the viscosity of helium II is at least 1,500 times smaller than that of helium I at normal pressure.

The experiments also showed that in the case of helium II, the pressure drop across the gap was proportional to the square of the velocity of flow, which means that the flow must have been turbulent. If, however, we calculate the viscosity, assuming the flow to have been laminar, we obtain a value of the order 10^{-9} C.G.S., which is evidently still only an upper limit to the true value. Using this estimate, the Reynolds number, even with such a small gap, comes out higher than 50,000, a value for which turbulence might indeed be expected.

We are making experiments in the hope of still further reducing the upper limit to the viscosity of liquid helium II, but the present upper limit (namely, 10^{-9} C.G.S.) is already very striking, since it is more than 10^4 times smaller than that of hydrogen gas (previously thought to be the fluid of least viscosity). The present limit is perhaps sufficient to suggest, by analogy with supraconductors, that the helium below the λ-point enters a special state which might be called a 'superfluid'.

As we have already mentioned, an abnormally low viscosity such as indicated by our experiments might indeed provide an explanation for the high thermal conductivity, and for the other anomalous properties observed by Allen, Peierls, and Uddin[2]. It is evidently possible that the turbulent motion, inevitably set up in the technical manipulation required in working with the liquid helium II, might on account of the great fluidity, not die out, even in the small capillary tubes in which the thermal conductivity was measured; such turbulence would transport heat extremely efficiently by convection.

P. KAPITZA.

Institute for Physical Problems,
Academy of Sciences,
Moscow.
Dec. 3.

---

[1] Burton, NATURE, **135**, 265 (1935); Wilhelm, Misener and Clark, *Proc. Roy. Soc.*, A, **151**, 342 (1935).

[2] NATURE, **140**, 62 (1937).

Flow of Liquid Helium II

A SURVEY of the various properties of liquid helium II has prompted us to investigate its viscosity more carefully. One of us[1] had previously deduced an upper limit of 10^{-4} C.G.S. units for the viscosity of helium II by measuring the damping of an oscillating cylinder. We had reached the same conclusion as Kapitza in the letter above; namely, that due to the high Reynolds number involved, the measurements probably represent non-laminar flow.

The present data were obtained from observations on the flow of liquid helium II through long capillaries. Two capillaries were used; the first had a circular bore of radius 0·05 cm. and length 130 cm. and drained a reservoir of 5·0 cm. diameter; the second was a thermometer capillary 93·5 cm. long and of elliptical cross-section with semi-axes 0·001 cm. and 0·002 cm., which was attached to a reservoir of 0·1 cm. diameter. The measurements were made by raising or lowering the reservoir with attached capillary so that the level of liquid helium in the reservoir was a centimetre or so above or below that of the surrounding liquid helium bath. The rate of change of level in the reservoir was then determined from the cathetometer eye-piece scale and a stop-watch; measurements were made until the levels became coincident. The data showing velocities of flow through the capillary and the corresponding pressure difference at the ends of the capillary are given in the accompanying table and plotted on a logarithmic scale in the diagram.

Capillary I		Capillary II			
T=1·07° K.		T=1·07° K.		T=2·17° K.	
Velocity (cm./sec.)	Pressure (dynes)	Velocity (cm./sec.)	Pressure (dynes)	Velocity (cm./sec.)	Pressure (dynes)
13·9	183·5	8·35	402	0·837	36·4
11·5	154·5	6·92	218	0·757	31·3
10·3	127·7	6·88	143	0·715	26·1
9·0	105·0	6·30	101	0·685	21·1
8·2	83·5	6·05	56	0·655	16·4
7·5	65·7	5·55	30	0·609	12·1
6·9	49·3	4·70	11·3	0·570	8·3
6·1	34·1	4·39	9·2	0·525	4·3
5·2*	20·3	3·92	13·0	0·433	0·9
4·5*	15·2	2·88	7·2		

The following facts are evident:

(*a*) The velocity of flow, q, changes only slightly for large changes in pressure head, p. For the smaller capillary, the relation is approximately $p \propto q^4$, but at the lowest velocities an even higher power seems indicated.

(*b*) The velocity of flow, for given pressure head and temperature, changes only slightly with a change of cross-section area of the order of 10^3.

(*c*) The velocity of flow, for given pressure head and given cross-section, changes by about a factor of 10 with a change of temperature from 1·07° K. to 2·17° K.

(*d*) With the larger capillary and slightly higher velocities of flow, the pressure-velocity relation is approximately $p \propto q^3$, with the power of q decreasing as the velocity is increased.

If, for the purpose of calculating a possible upper limit to the viscosity, we assume the formula for laminar flow, that is, $p \propto q$, we obtain the value $\eta = 4 \times 10^{-9}$ C.G.S. units. This agrees with the upper limit given by Kapitza who, using velocities of flow considerably higher than ours, has obtained

the relation $p \propto q^2$ and an upper limit to the viscosity of $\eta = 10^{-9}$ C.G.S. units.

The observed type of flow, however, in which the velocity becomes almost independent of pressure, most certainly cannot be treated as laminar or even as ordinary turbulent flow. Consequently any known formula cannot, from our data, give a value of the 'viscosity' which would have much meaning. It may be possible that the liquid helium II slips over the surface of the tube. In this case any flow method would be incapable of showing the 'viscous drag' of the liquid.

With regard to the suggestion that the high thermal conductivity of helium II might be explained by turbulence, we have calculated that the flow velocity necessary to transport all the heat input over the observed temperature gradient in the Allen, Peierls and Uddin experiments[2] is about 10^4 cm./sec. On the other hand, the greatest flow velocity produced by manipulation and by the pressure difference along the thermal conduction capillary will not be likely to be greater than 50 cm./sec. It seems, therefore, that undamped turbulent motion cannot account for an appreciable part of the high thermal conductivity which has been observed for helium II.

J. F. ALLEN.
A. D. MISENER.

Royal Society Mond Laboratory,
Cambridge.
Dec. 22.

---

[1] Burton, E. F., NATURE, **135**, 265 (1935).

[2] Allen, Peierls and Uddin, NATURE, **140**, 62 (1937).

Some Experiments at Radio Frequencies on Supraconductors

MEASUREMENTS were made on an extruded tin wire carrying an alternating current of a frequency of about 200 kilocycles per second superposed upon a direct current. The resulting magnetic field at the surface of the wire was thus caused to pulsate cyclically.

Figure 3. Shown are the famous papers of Kapitza (left) and Allen and Misener (right), which appeared back-to-back in *Nature* on January 8, 1938. (Reprinted by permission of Macmillan Publishers Ltd: *Nature* [16, 17], copyright 1938.)

Nobel Prize with Allen, but only 'off the record'. However, David Shoenberg, a close friend and student of Kaptiza, has written to the author that a Russian physicist, who knew Kaptiza well, said this story was true. Why might Kapitza refuse to share the Nobel Prize with Allen? Several plausible reasons are discussed in [2].

5. A brief history of our theoretical understanding of superfluidity since 1938

It is useful to first give a one paragraph summary of BEC in the period 1938–1960 (for more details, see [19]). London (1938) first suggested that the transition at $T = 2.18$ K in liquid ^{4}He was due to the formation of a BEC of ^{4}He atoms. Tisza (1938) then suggested that the spectacular superfluidity effects observed in 1938 were related to the coherent motion of the Bose condensate. It took decades to 'put clothes' on this latter concept. Landau (1941) developed a very successful two-fluid theory of superfluid ^{4}He based on elementary excitations of the system. However, Landau's beautiful theory made no mention of BEC (or Bose statistics or even atoms!). This was puzzling for many years. In the period 1957–64, however, many-body theorists finally developed a quantum-field formalism which could be used to show how a Bose condensate was the microscopic basis of the superfluidity in liquid ^{4}He and of Landau's phenomenological theory. This unified the work of London, Tisza and Landau (shown in figure 4).

Early in 1938, London [20] came up with the idea that the phase transition at 2.18 K was related to the discredited phenomenon of Bose–Einstein condensation (BEC). Einstein's work in 1925 predicting BEC was not appreciated, partly because second-order phase transitions in general were not yet really understood before 1937. In particular, Ehrenfest and his student Uhlenbeck at Leiden erroneously argued in 1927 that Einstein's prediction of a BEC was based on an incorrect approximation of a momentum sum over discrete states by an integral.

Tisza (both London and he were working in Paris in 1938) quickly took London's BEC idea further [22] and introduced a two-fluid model in which the superfluid component was the analogue of the Bose–Einstein condensate introduced by Einstein. Tisza conjectured that it moved without friction or viscosity since it involved the coherent motion of a large number of atoms in the same single-particle quantum state.

London and Tisza were the first to talk about a quantum liquid. However, the only concrete model they had for calculations was a ideal Bose gas. Landau felt this starting point (as well as BEC) was not valid in a liquid, and developed a different approach in 1941. It would take until 1957 to realize that BEC was indeed the correct microscopic basis for superfluid helium and led to the Landau two-fluid hydrodynamic equations. Of course, if BEC in gases had been discovered in 1938 instead of 1995, the correctness of the London-Tizsa picture would have never been in question.

Figure 4. From left to right, London, Tisza and Landau. Their theoretical studies published in the period 1938–41 established the essential ideas of our modern understanding of superfluidity in liquid ^{4}He. (Photo of London from [21], by permission of the family of Fritz London.)

Figure 5. Erwin Schrödinger and his assistant London in Berlin in 1928, both apparently having a good time. (From [26], by permission of the family of Fritz London.)

The difference between Bose gases and liquids is shown in the following table:

	Bose liquid	Bose gas
Easy to measure	superfluidity	BEC
Hard to measure	BEC	superfluidity

'Thinking Big' is the perceptive title of an article by Anderson [23], who argues that London is not appreciated enough as the pioneer in understanding how quantum theory could work and be observed on the macroscopic scale. London was well ahead of his time. In contrast to Bohr and other theorists in the 1930s, London thought that quantum theory was correct at all scales and that superconductivity in metals and superfluidity in liquid ^{4}He were especially interesting precisely because they illustrated macroscopic quantum effects. London was a research assistant with Schrödinger in 1928 (see figure 5) when the latter still felt that a wavefunction might represent something 'real'. Was this the birth of London's later concept of a 'macroscopic' wavefunction? It is very fitting that the highest award in low temperature physics is the Fritz London Memorial Prize.

The two-fluid hydrodynamics of Landau [24] was based on quantizing the hydrodynamic theory of a classical liquid. Landau with great brilliance 'stitched' a new superfluid degree of freedom to the usual equations of fluid dynamics. The new quantum superfluid component had a velocity which was assumed to be irrotational and also carried no entropy. The new two-fluid hydrodynamic equations predicted a new type of hydrodynamic oscillation, called second sound, which involves an out-of-phase motion of the superfluid and normal fluid components [25].

The structure of the Landau two-fluid equations is now realized to be universal if there is an underlying Bose condensate. The only difference between superfluid ^{4}He and superfluid gases is in the evaluation of the local thermodynamic functions, such as the pressure, entropy, etc. Only these quantities require a microscopic theory of the thermal excitations of the particular system of interest.

The second great contribution of Landau's paper [24] is very specific to liquid ^{4}He, namely he postulated bosonic phonon–roton quasiparticle excitations as a description of the normal fluid. This enabled Landau to calculate the various thermodynamic quantities that occurred in his generic two-fluid equations [24, 25]. The Landau two-fluid equations with the phonon–roton quasiparticle spectrum introduced in 1947 gives a very satisfactory description of superfluid helium. The Landau theory was so successful that BEC was largely ignored in discussions about liquid ^{4}He. At LT conferences before the discovery of BEC in trapped Bose gases in 1995, one often heard the comment: BEC–who needs it?

However, Landau's theory is not a microscopic theory. The fact that ^{4}He atoms are bosons is never used. It seems clear that in 1941 Landau thought there was only 'one kind' of quantum liquid, which corresponded to the quantized hydrodynamics of a classical liquid. Our current view that BEC forms the microscopic basis of Landau's theory of superfluidity developed from work by Bogoliubov [27] and Beliaev [28], both pictured in figure 6. Beliaev's field-theoretic approach allowed one to separate out the dynamical role of a Bose condensate even in a strongly interacting liquid like superfluid ^{4}He. As we have noted above, the conceptual basis for superfluidity as a consequence of a Bose condensate was settled in the period 1957–64 (for more details, see [19]). Later this was directly confirmed by Monte Carlo calculations [34], which showed that both the superfluid and condensate densities become finite at the same temperature $T_c = 2.18$ K. It was a great triumph of theoretical physics, although of not much

Figure 6. From left to right, Bogoliubov, Beliaev and Gorkov. Beliaev and Gorkov set up the field-theoretic formalism for understanding superfluidity (in both Bose and Fermi systems) in terms of anomalous propagators. For reasons that are not clear, none of these theorists received the Nobel Prize in Physics for their seminal work. (Photo of Bogoliubov from [32], by permission of Springer; photo of Gorkov used by permission of Florida State University.)

interest to the experimental community who tended to work on problems that could be solved within the Landau paradigm.

It is puzzling why Landau appears to have resisted the idea that BEC was the microscopic basis of his theory of superfluidity. However, at the end of his second great paper in 1957 on interacting Bose-condensed gases [28], we note that Beliaev concludes with: *The difference between liquid helium and a non-ideal Bose gas is only a quantitative one, and no qualitatively new phenomenon is expected to arise in the transition from gas to liquid.* It is very significant that at the end of this paper, Beliaev thanks Landau for 'discussion of these results'.

6. Let there be light

The creation of a BEC in trapped atomic gases in 1995 [29] changed our views on BEC and its relation to superfluidity very quickly. Finally, we now had a superfluid Bose gas to compare with a superfluid Bose liquid. Figure 7 shows the key experimentalists whose work led to the discovery of BEC in trapped atomic gases.

Atomic Bose condensates involve millions of atoms all occupying the identical single-particle quantum state. They can do this because the atoms are bosons, and the exclusion principle does not hold. As a result, millions of atoms are described by a macroscopic single-particle wavefunction $\Phi(\mathbf{r})$, which corresponds to a macroscopic de Broglie 'matter wave'. These matter waves describe a new kind of condensed matter, which is not a solid, liquid or a gas. At finite temperatures, however, atoms are thermally excited out of the Bose condensate to form a thermal gas of atoms, the analogue of the normal fluid in superfluid ^{4}He. The excitation spectrum in trapped dilute Bose gases is well described by the Hartree–Fock approximation (at all but the lowest temperatures), rather than the phonon–roton excitations appropriate to superfluid ^{4}He. This has the consequence that in dilute Bose-condensed gases, the superfluid component can be identified with the Bose condensate and the normal fluid with the thermal cloud. This means there is no 'quantum depletion' of the condensate. In fact, very recent experimental work on both atomic and molecular Bose gases is now giving us access to strongly interacting Bose-condensed gases [30, 31] which are more analogous to superfluid ^{4}He.

Figure 7. From left to right, this shows J Walraven, R Hulet, W Ketterle, E Cornell and D Kleppner celebrating the 10th anniversary of the creation of a BEC in atomic gases at the BEC 2005 Workshop in San Feliu, Spain. With C Wieman, these experimentalists played the key role in the long march which finally led to the discovery of BEC in 1995 (photo by permission of the author).

Even more interesting is the recent study of superfluidity in trapped ultracold Fermi gases. The pioneering work of BCS–Gorkov on superconductivity and Beliaev on BEC has now been beautifully joined together in trapped two-component atomic Fermi gases. As suggested by Leggett in 1980 (shown in figure 8), by increasing the attractive interaction between fermions, one has a smooth crossover from a standard weak-coupling BCS phase to a Bose-condensed gas of interacting bosonic molecules. A molecular BEC was first produced and detected by three groups in November 2003 [33, 35, 36], using the fact that one can easily adjust the strength of inter-atomic interactions in Fermi gases. This allows one to move smoothly from a BCS phase to the molecular BEC phase (for more details and references, see chapter 17 of [29]).

In 1957, Bardeen, Cooper and Schrieffer (BCS) solved the mystery of superconductivity in metals based on the formation

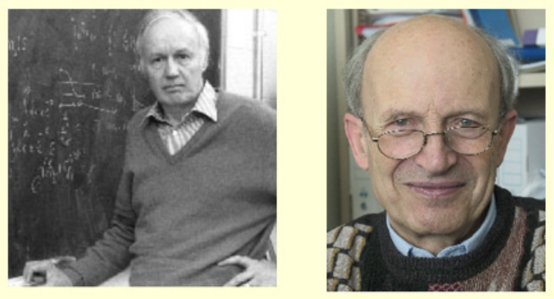

Figure 8. From left to right, Leggett and Nozières, who made pioneering contributions to understanding the BCS–BEC crossover in superfluid Fermi gases. (Photo of Leggett by permission of the Department of Physics, University of Illinois; photo of Nozières by permission of the Institut Laue-Langevin.)

of Cooper pairs [37]. However the initial formulation hid the essential physics, leading to the erroneous statement 'our theory is not analogous to a Bose–Einstein transition' (footnote 18 of the BCS paper). This comment led to a long delay in understanding the nature of the BCS phase. It should be noted that within a few months, Gorkov [38] showed that the BCS theory corresponded to a simple mean-field theory, but in addition to the usual Hartree–Fock terms, one had to include a novel off-diagonal mean field describing the effects of (quoting Gorkov) 'a sort of Bose condensate of Cooper pairs'. Gorkov's work in Moscow was done in close proximity to Beliaev, who was introducing the analogous formalism for Bose superfluids at the same time. However, Gorkov's comment was not picked up in the literature. In later years, Bardeen also emphasized that BCS was built on the idea of a Bose condensate of Cooper pairs (see epilogue of [26]).

Using an atomic Feshbach–Verhaar resonance, one can easily tune the s-wave scattering length and experimentally study the BCS–BEC crossover phenomenon in trapped two-component Fermi gases. The molecules are weakly bound but are very stable because 3-body decay is forbidden since fermions in the same atomic hyperfine state obey the exclusion principle and hence repel each other (for further discussion, see [29]).

The bound states in interacting Fermi gases are bosonic and hence can form a molecular BEC, just like Bose atoms can. As a result, in trapped Fermi gases, the well-known description of a Bose condensate will appear once again, except that it can now describe a Cooper pair condensate, immersed in the gas of unpaired fermions (BCS region of weak interactions) or a molecular Bose condensate (BEC region of strong interactions). The BEC phase was 'hiding' in the original BCS equations derived in 1957! In the extreme limit, all N Fermi atoms pair up to form $\frac{1}{2}N$ bound states. This is the BEC limit of the interacting Fermi gas. It is effectively a Bose-condensed gas of $\frac{1}{2}N$ molecules, each with mass $M = 2m$.

What is the relation between superconductivity and superfluidity? The standard BCS equations assume that all the Cooper pairs are Bose-condensed in the zero-momentum centre of mass state. As the attractive interaction increases in strength, however, the Cooper pairs become stable two-particle states. As the temperature is increased, more and more of these Cooper pair bound states are excited out of the condensate into states of finite (centre of mass) momentum and behave like a gas. In this improved theory, the superfluid transition corresponds to the temperature where the bound state condensate is completely depleted, just like any dilute Bose gas! Nozières was the first to calculate the superfluid transition temperature in 1985 taking this depletion into account as one passed through the BCS–BEC crossover [39].

While I was on sabbatical at Grenoble in 1981, I remember when Nozières rushed in one day to tell us that, for a strong attractive interaction between the fermions, the BCS theory transition temperature of 1957 reduced to the BEC formula first derived by Einstein in 1925. Philippe was very excited, as he should have been! He also realized that the rival theory to BCS in 1957 due to Schafroth, Butler and Blatt [40] corresponded to the BEC side of an extended BCS theory, while the original paper by BCS [37] had only considered the BCS side in the extreme limit of very weak attractive interactions. Both kinds of superfluidity were just two faces of the same phenomenon. London would have been very happy!

The Landau two-fluid equations describe the dynamics of a superfluid coupled to a normal fluid at finite temperature, which has been brought into 'local hydrodynamic' equilibrium by rapid collisions. As noted earlier, these equations are an extension of ordinary fluid dynamics described in terms of the usual hydrodynamic variables, but now include a new superfluid degree of freedom. The two-fluid equations describe collective oscillations of frequency ω with a period T only if the appropriate atomic collision time τ satisfies the local equilibrium condition:

$$\tau \ll T \Rightarrow \omega\tau \ll 1.$$

Using a Feshbach–Verhaar resonance, we can now produce a strongly interacting Bose gas of stable molecules [31, 33, 35, 36], which can reach local equilibrium needed for two-fluid hydrodynamics to be valid. This is the precise analogue of what Landau studied in 1941 in liquid helium. To achieve this two-fluid hydrodynamics is one of the major challenges in future research on ultracold quantum gases.

7. Conclusions: superfluid ^{4}He comes out of the cold

Since the discovery in 1938, superfluid helium has been thought to be a very unique quantum fluid. The study of dilute superfluid ^{3}He–^{4}He mixtures never added much to our understanding of superfluidity and its relation to BEC. However, exciting recent developments (in the last five years) in trapped Bose and Fermi gases have given us new strongly interacting superfluid gases which are starting to resemble superfluid helium, with strong depletion of the condensate fraction even in a very low density gas. Superfluid helium, that most amazing fluid, now has some brothers and sisters. In 2008, it has finally come out of the cold!

Acknowledgments

I would like to acknowledge many useful discussions with S Balibar on the discovery of superfluidity. My research is funded by NSERC of Canada.

References

[1] van Delft D 2007 *Freezing Physics: Heike Kamerlingh Onnes and the Quest for Cold* (Amsterdam: Edita KNAW)
[2] Griffin A 2008 *Phys. World* **21** 27
[3] Balibar S 2007 *J. Low Temp. Phys.* **146** 441
[4] Griffin A 2003 *A Century of Nature* ed L Garwin and T Lincoln (Chicago, IL: University of Chicago Press) p 51
[5] Lifshitz E M 1958 *Sci. Am.* **198** 30
[6] Keesom W H and Wolfke M 1928 *Proc. R. Acad. Amst.* **31** 90
[7] Keesom W H and Clusius K 1932 *Proc. R. Acad. Amst.* **35** 307
[8] Griffin A 2005 *Phys. Can.* **61** 31
[9] McLennan J C 1923 *Nature* **112** 135
[10] McLennan J C, Smith H D and Wilhelm J O 1932 *Phil. Mag.* **14** 161
[11] Khalatnikov I M 1964 *International Science and Technology* (November) p 61
[12] Boag J W, Rubinin P E and Shoenberg D 1990 *Kapitza in Cambridge and Moscow. Life and Letters of the Russian Physicist* (Amsterdam: North-Holland)
[13] Rubinin P E 1997 The discovery of superfluidity. Letters and documents *Phys.–Usp.* **40** 1249
[14] Allen J F, Peierls R and Uddin Z 1937 *Nature* **140** 62
[15] Burton E F 1935 *Nature* **135** 265
[16] Allen J F and Misener A D 1938 *Nature* **141** 75
[17] Kapitza P 1938 *Nature* **141** 74
[18] Wilhelm J O, Misener A D and Clark A R 1935 *Proc. R. Soc.* A **151** 342
[19] Griffin A 1999 *Bose–Einstein Condensation in Atomic Gases* ed M Inguscio, S Stringari and C E Wieman (Amsterdam: IOS Press) p 1
[20] London F 1938 *Nature* **141** 643
London F 1938 *Phys. Rev.* **54** 947
[21] London F 1954 *Superfluids* vol II (New York: Wiley)
[22] Tisza L 1938 *Nature* **141** 913
Tisza L 1940 *J. Phys. Radium* **1** 164
Tisza L 1940 *J. Phys. Radium* **1** 350
[23] Anderson P W 2005 *Nature* **437** 625
[24] Landau L D 1941 *J. Phys. USSR* **5** 71
Landau L D 1947 *J. Phys. USSR* **11** 91
[25] Khalatnikov I M 1965 *An Introduction to the Theory of Superfluidity* (New York: Benjamin)
[26] Gavroglu K 1995 *Fritz London* (New York: Cambridge University Press)
[27] Bogoliubov N N 1947 *J. Phys. USSR* **11** 23
[28] Beliaev S T 1958 *Sov. Phys.—JETP* **7** 289
Beliaev S T 1958 *Sov. Phys.—JETP* **7** 299
[29] Pethick C and Smith H 2008 *Bose–Einstein Condensation in Dilute Gases* second edn (New York: Cambridge University Press)
[30] Papp S B, Pino J M, Wild R J, Ronen S, Wieman C E, Jin D S and Cornell E A 2008 *Phys. Rev. Lett.* **101** 135301
[31] Inada Y, Horikoshi M, Nakajima S, Kuwata-Gonokami M, Ueda M and Mukaiyama T 2008 *Phys. Rev. Lett.* **101** 180406
[32] Salem A 1992 *Theor. Math. Phys.* **92** 817
[33] Greiner M, Regal C A and Jin D S 2003 *Nature* **426** 537
[34] Pollock E L and Ceperley D M 1987 *Phys. Rev.* B **36** 8343
[35] Jochim S, Bartenstein M, Altmeyer A, Hendl G, Riedl S, Chin C, Denschlag J H and Grimm R 2003 *Science* **302** 301
[36] Zwierlein M W, Stan C A, Schunck C H, Raupach S M F, Gupta S, Hadzibabic Z and Ketterle W 2003 *Phys. Rev. Lett.* **91** 250401
[37] Bardeen J, Cooper L N and Schrieffer J R 1957 *Phys. Rev.* **108** 1175
[38] Gorkov L P 1958 *Sov. Phys.—JETP* **7** 505
[39] Nozières P and Schmitt-Rink S 1985 *J. Low Temp. Phys.* **59** 195
[40] Schafroth M R, Butler S T and Blatt J M 1957 *Helv. Phys. Acta.* **30** 93