

WHO DISCOVERED SUPERFLUIDITY?

SÉBASTIEN BALIBAR

*Laboratoire Pierre Aigrain, Department of Physics, École Normale Supérieure,
Paris, France*

In 1938, quantum physics jumped from the microscopic world of atoms to the macroscopic one of visible matter. At the origin of this breakthrough, Fritz London and Laszlo Tisza who initiated the theory of superfluidity. They were two refugees working temporarily in Paris and their work had been triggered by experiments simultaneously performed by Piotr Kapitza in Moscow and by Jack Allen and his student Don Misener in Cambridge. In 1941, Lev Landau improved Tisza's model. Among these six great scientists, only Landau and Kapitza received the Nobel prize. This article describes their respective contributions. It is also an opportunity to consider how refugees worked in the storm of years 1938-1945.

1 Introduction

In December 1937, J. F. Allen and A. D. Misener in Cambridge and simultaneously P. Kapitza in Moscow discovered the superfluidity of liquid helium. In March 1938, F. London proposed that superfluidity was connected to a quantum phenomenon called "Bose-Einstein condensation" (BEC). He was right so that quantum mechanics suddenly appeared as being at play at the macroscopic scale of our visible world, not only at the microscopic scale of the inside of atoms.

This major discovery was made possible by the progress of low-temperature techniques, especially the construction of helium liquefiers. London's ideas were soon developed by L. Tisza who invented the "two-fluid model" to explain most of the helium properties that were known at that

time. In 1941, L. D. Landau made further progress in the understanding of superfluidity but, surprisingly, he never agreed with London and Tisza on the possible relation of superfluidity to BEC. Among these six great physicists, only Landau and Kapitza received the Nobel Prize.

The history of this discovery is quite interesting because it illustrates the way how modern science progresses, especially how controversies are solved, also because this discovery was made at a time when the world was torn apart by conflicts and wars. Seventy years later, superfluidity has been found in several other quantum fluids. It appears as closely related to superconductivity, another macroscopic property of quantum matter, and superfluid helium can be used to cool down matter at an industrial scale.

2 Before the discovery

Superfluidity has a prehistory, which starts with Heike Kamerlingh Onnes liquefying helium gas for the first time in 1908 at the University of Leiden (The Netherlands). In 1932 and at the University of Toronto (Canada), John McLennan observed that, when pumping on liquid helium to cool it down, it stopped boiling below a reproducible temperature of 2.2 K where it suddenly became still as if some inner order had taken place (see [fig. 1](#)). This apparent ordering was confirmed in Leiden in 1935 by Willem Keesom and his daughter Ania, who measured the specific heat of this cold liquid. They found that, below a λ -shape singularity at 2.2 K, the specific heat decreased sharply. This was a strong indication of a phase transition where some kind of order was indeed taking

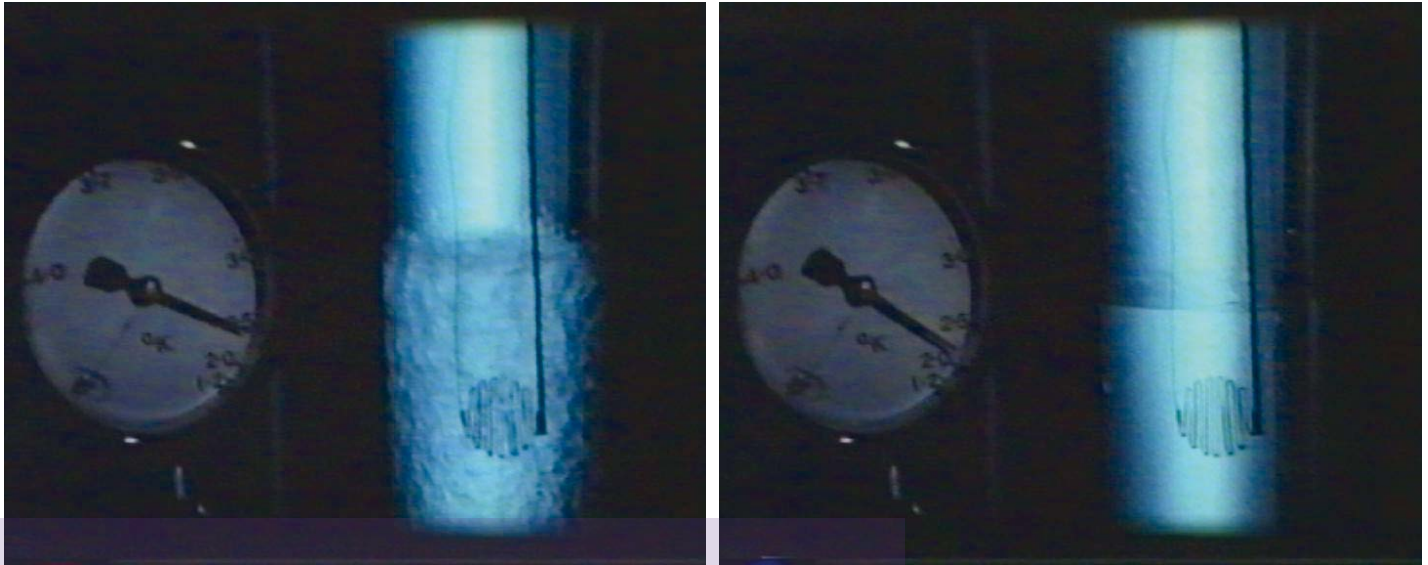


Fig. 1 Two pictures from the historical movie made by J. F. Allen and J. M. G. Armitage in 1972, which show liquid helium boiling at 2.3 K (left) and not at 2.1 K (right) when heated by a resistance. Reproduced with permission from the School of Physics & Astronomy, University of St Andrews. © University of St Andrews.

place. They called this temperature and this phenomenon, respectively, the λ -point and the λ -transition.

In 1935 again, Willem and Ania Keesom also measured the thermal conductivity of liquid helium. They found that, below the “ λ -point”, liquid helium conducted heat better than copper, a rather surprising result that was later confirmed at Cambridge University by Jack Allen, Rudolf Peierls and Zaki Uddin. This high thermal conductivity explained why liquid helium was not boiling: the temperature was so homogeneous that liquid helium had no hot spots where gas bubbles could nucleate, it was only evaporating from its free surface¹.

One possible explanation for this very high thermal conductivity was that it occurred not by classical diffusion but by convection in a liquid whose viscosity could be very small. Obviously, the competition at that time was between Toronto and Leiden, the first two places where helium gas was liquefied. In 1935 once more, but at Toronto this time, J. O. Wilhelm, A. D. Misener and A. R. Clark discovered that the viscosity of liquid helium started decreasing strongly below 2.2 K. For that, they had measured the damping of an oscillating cylinder immersed in liquid helium. The damping was decreasing below the λ -point. With all classical liquids, cooling down increases the viscosity and usually produces

crystallization. Nothing like that was observed with liquid helium: it seemed to be never freezing and its apparent viscosity was decreasing. This is probably what triggered the historical work of Piotr Kapitza in Moscow and that of Jack Allen who had attracted in Cambridge the young student who had made preliminary measurements of this viscosity in Toronto, A. D. Misener.

3 The experimental discovery of superfluidity

On January 8th, 1938, the review *Nature* published two letters face to face.

The first one, on page 74 of the issue, was entitled “*Viscosity of Liquid Helium below the λ -point*” and signed “Piotr Kapitza, Institute for Physical Problems, Moscow, Dec. 3” (see fig. 2). Kapitza had observed the flow of liquid helium through a very thin slit between two well-polished disks. Above 2.2 K, liquid helium was not flowing but below this transition temperature the flow was so fast that Kapitza could only propose an upper limit for its viscosity. He suggested that the flow was turbulent and hoped to reduce the upper limit he had found. At the end, Kapitza wrote that “... *by analogy with superconductors, the helium below the λ -point enters a special state which might be called superfluid*”. Kapitza had invented the word “superfluid” and the analogy with superconductors was correct although superconductivity had to wait until the BCS theory of John Bardeen, Leon Cooper and Robert Schrieffer in 1957 to be understood as a superfluidity of electron pairs.

¹ 40 years later, when preparing my doctorate, I discovered that the evaporation of liquid helium was a quantum phenomenon at low temperature, which was analogous to Einstein's photoelectric effect as had been predicted by P. W. Anderson. See [1].



Fig. 2 On the left: Jack Allen in the Mond laboratory (Cambridge), credits: Cavendish lab. On the right: Piotr Kapitza in front of one of his collaborators in his Institute for Physical Problems (Moscow).

The second letter, on page 75 of the January 8th issue of *Nature*, was entitled “Flow of liquid helium II” and signed “J. F. Allen and A. D. Misener, Royal Society Mond Laboratory, Cambridge, Dec. 22” (see fig. 2). It described a series of quantitative measurements of the flow of liquid helium in thin capillaries with inner sizes between 10 and 500 micrometres. Here too, liquid helium was found to flow much faster after cooling it down below the λ -point in a state called “helium II”. Most interestingly, Allen and Misener found that the flow speed was nearly independent of the capillary inner size and of the applied pressure. This behaviour was definitely non-classical. They concluded with: “*it seems therefore that any known formula cannot, from our data, give a value of the ‘viscosity’ which would have much meaning*”.

One has to distinguish between the experimental discovery of superfluidity and the theoretical one.

Concerning the experimental evidence, it is usually dated on January 8th 1938, the publication date. Some people considered that the 19 days difference in the submission date was sufficient to attribute the discovery to Kapitza only. After looking at letter exchanges and notebooks, it became clear that all the authors knew that they were competing with each other but none of them knew the results of the other [2]. These two works were independent: their methods were different and the results too. Furthermore, to work on liquid helium at that time required to start every morning by liquefying helium, so that these experiments lasted for much more than 19 days. In both places they obtained preliminary results during the last months of 1937. When

neglecting the contribution of Allen and Misener and attributing the discovery to Kapitza only, some people may have been influenced by the importance of inventing the word “superfluid”, or by the fact that the Nobel Academy crowned Kapitza alone, or perhaps that, in Cambridge, Allen was using a liquefier that had been built by Kapitza before he was retained in the USSR. However, it seems to me that the first person who demonstrated quantitatively that the hydrodynamics of liquid helium required a non-classical theory was Jack Allen with his student. In 1938, Kapitza was still thinking in terms of a small viscosity. In summary, I attribute the experimental discovery of superfluidity to both Kapitza and Allen. Fortunately, it is generally accepted today.

As for the reasons why Kapitza obtained his Nobel prize in 1978, that is with a long delay, there are rumours saying that Kapitza would have never accepted to share it with his competitors, perhaps because he had suffered so much from being forced to leave his liquefier in Cambridge, where his competitors used it [3].

What happened more precisely to Kapitza?

Kapitza was born in Kronstadt (Russia) in 1894 and, in 1921, he had joined Ernest Rutherford in Cambridge. There he was so successful that the Royal Society had built for him the “Mond Laboratory” with the financial support of Ludwig Mond, the president of ICI, the Imperial Chemical Industries. There he worked on magnetism and built a new type of helium liquefier which started working on April 19th, 1934. But in September 1934 it was the centenary of Mendeleev and an opportunity for Kapitza to go back to USSR and visit

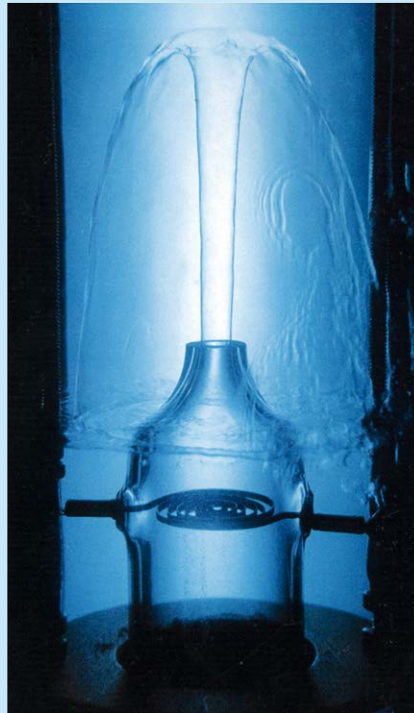


Fig. 3 A photograph of the “fountain effect” taken by J. F. Allen and J. M. G. Armitage in 1972 at St Andrews University (Scotland). Heat is produced by the spiral shape electrical resistance in the middle of the bottle. The bottle is immersed in a superfluid reservoir and closed on its bottom end by a porous plug. Reproduced with permission from the School of Physics & Astronomy, University of St Andrews. © University of St Andrews.

his mother and friends. However he was summoned by the soviet power and retained there. Stalin wanted him to work for the development of USSR. After some temptation of working on the thermodynamics of muscles with Ivan Pavlov, the famous physiologist studying the behaviour of dogs, he asked Stalin to build a new building for his research on helium and to contact Ernest Rutherford to buy his equipment from Cambridge University. Rutherford accepted but kept the precious liquefier in Cambridge so that he could hire new young scientists (Jack Allen and Rudolf Peierls) to work on the newly opened field of liquid helium. Kapitza needed help and he was also allowed to invite two engineers (Henry Pearson and Emil Laurmann) and one of his former students (David Schoenberg of Russian origin). As a result, the “Kapitza Institute” –as the Institute of Physical Problems was soon called in Moscow– was finished building in 1937 and a new helium liquefier ready to produce its first droplets on February 22nd 1937. It took Kapitza less than a year to send his results to *Nature* but he had gone through a very hard period. On April 1935 he had written to his wife: “*I am ready to tear my hair and go berserk. With my instruments, with my ideas, in my laboratory other people live and work, and I do not understand whoever needs this. I want to shout and break chairs. Sometimes I feel my mind is going...*” [4]. He knew that Jack Allen was using his liquefier in Cambridge and he would have strong reasons to be upset if he had to share a Nobel

prize with Jack Allen. Anyhow, I hardly believe that the Nobel committee negotiates its prizes with potential laureates. The reason for nominating Kapitza alone was probably that, after the discovery of January 1938, the contribution of Kapitza was significantly more important than that of Jack Allen, and, in 1978, they had an opportunity to add only one name to those of Penzias and Wilson who had discovered another low temperature: the 2.7 K of the cosmic background radiation. Still, I repeat that the two main authors of the experimental discovery of superfluidity are Jack Allen and Piotr Kapitza.

4 London and the theory of superfluidity

What about the theoretical discovery? It was triggered by one more experiment by Jack Allen, this time with Harry Jones, a theorist of metal properties. They had discovered another surprising property of liquid helium, which they had published in *Nature* on February 5th 1938, only one month after the studies of liquid-helium flow. They plunged a bottle in a liquid-helium reservoir. This bottle was open on its top side but connected to the reservoir on its bottom side thanks to a thin capillary (see fig. 3 where Jack Allen later replaced the capillary by a porous plug). They discovered that heating the inside with an electrical resistance produced a fountain of superfluid helium springing out from the top side.

Once more, no classical theory could explain such an



Fig. 4 Berlin 1928 : Erwin Schrödinger on the left and Fritz London on the right (personal collection of Laszlo Tisza).

astonishing behaviour. Superfluid helium was definitely non-classical and Fritz London searched for a completely new explanation.

Fritz London had arrived in Paris with his wife Edith Caspary in September 1936. They had escaped from Germany as many academics with a Jewish origin, in 1933 when Hitler took power. London had been attracted to Oxford by an astonishing character, Frederik Lindemann who wanted to create there a strong activity on the newly born Low Temperature Physics. Frederik Lindemann was the second son of an Alsatian engineer. After studying in Berlin, he became an engineer in aeronautics, and despite his German name and German accent he was a British citizen. He had become famous as a pilot during World War I but, in the thirties, he was the director of the Clarendon Laboratory in Oxford. As such, at the beginning of 1933, he decided to recruit well-recognized physicists in Berlin and in Breslau. Among them were Erwin Schrödinger, Franz Simon, Kurt Mendelssohn², Nicholas Kürti, Heinz London and his brother Fritz London. Lindemann was also xenophobic, vegetarian, non-smoking and drinking tea. This was all the contrary of Winston Churchill but in 1939 he became Churchill's personal adviser, he was ennobled as Lord Cherwell and called "The prof" or

"Lord Berlin" depending on appreciation [5].

Fritz London had hesitated before accepting Lindemann's offer but he was already very well recognized thanks to his understanding of the hydrogen molecule. Together with Walter Heitler in 1927 (Fritz London was 27 (fig. 4) and Heitler 23 years old!), they had used Schrödinger's equation to calculate the attraction between H atoms and their binding as an H₂ molecule. With this famous work, they had founded quantum chemistry. Lindemann found support from the Imperial Chemical Industries, a fellowship for three years. Finally Fritz London accepted to move to Oxford.

London's life was peaceful in Oxford except that he had not been able to bring his mother with him, so that she was still in danger, facing the antisemitism of the Nazis. But the fellowship from the ICI ended in 1936 and there was apparently nothing else to support him. His British hosts had not anticipated that Nazism could last for a long time. Fritz London had thus to look for another country to take refuge.

He got offers from Paris, Jerusalem and the United States. He then followed the advice of Walter Adams, the secretary of the Academic Assistance Council who had already helped him and who was in close contact with a similar organism in France, the "Comité d'accueil et d'organisation du travail des scientifiques étrangers". This Comité was run by Louis Rapkine, a biologist of Byelorussian origin who was deeply involved in the drastic problem of welcoming foreign

² Franz Simon and Kurt Mendelssohn were cousins of the composers Felix and Fanny Mendelssohn.

scientists in France. Rapkine had obtained support from French intellectuals like Jean Perrin (Nobel prize 1926), Paul Langevin, Frédéric and Irène Joliot-Curie (Nobel prizes 1935). Most of them were engaged with the "Front Populaire" the political coalition which had won the 1936 elections and this committee was able to offer immediately a one-year fellowship to Fritz London. Then London obtained a stable position from a new public institution, the CNRS at its very early days.

Soon after reading Allen's new article on the "fountain effect", Fritz London had a revolutionary idea: superfluidity could probably be understood in terms of the "Bose-Einstein condensation" a phenomenon "*which had rather got the reputation of having a purely imaginary existence*". In 1924, by extending the work of the Bengali theorist Satiendra Nath Bose, Einstein had predicted that a gas of quantum particles should "condense" at low enough temperature on a single quantum state. This very peculiar type of condensation meant that such atoms would become undistinguishable from one another and form a macroscopic wave of matter where their momentum is the same so that they adopt the same behaviour. For this, the atoms had to obey Bose statistics, which requires a certain parity that is different from the other category of quantum particles, namely the Fermi statistics. It is a subtle question of symmetry: Bose particles are even while Fermi particles are odd. Today we understand the Bose-Einstein condensation (BEC) as a new kind of ordering which appears in the momentum space, not in the real space as when atoms crystallize on a periodic network. But at that time, it looked unlikely so that Einstein himself wrote to his friend Paul Ehrenfest the famous question: "*die Theorie ist hübsch aber ob auch etwas wahres dran ist?*" (*the theory is nice but is there anything true in it?*). Ehrenfest had moved to Leiden where Lorentz attracted him to take his own chair when he retired.

Concerning this surprising prediction of a new kind of quantum order, the situation had not evolved very much since 1924. George Uhlenbeck, a student of Ehrenfest, had raised some criticism on Einstein's calculation. But in November 1937, a conference was organized in Amsterdam to celebrate the centenary of van der Waals where Ehrenfest, Uhlenbeck, Kramers and Einstein discussed different types of condensation. Fritz London was also there and at the end of the discussion, Uhlenbeck withdrew his objection. Three months later, when thinking about the superfluidity of liquid helium, London calculated the temperature at which a Bose-Einstein condensation could take place if it were an ideal gas and he found 3.09 K, a value that was not so different from the lambda temperature 2.2 K. Then he calculated the temperature variation of the specific heat and found a singularity that was also similar to what had been measured.

He hesitated but his idea was already spreading in the British community so that he finally sent a short letter, once more to *Nature*. Its title was "*The λ -Phenomenon of Liquid Helium and the Bose-Einstein Degeneracy*" and he signed it "Fritz London, Institut Henri Poincaré, Paris, March 5". He was conscious that reducing a liquid to an ideal gas was a very rough approximation, even if the density of liquid helium was very low as a consequence of large quantum fluctuations. But he wrote: "*it is difficult not to imagine a connexion with the condensation phenomenon of the Bose-Einstein statistics*". A few years before, the two London brothers had already considered that superconductivity could be explained as a macroscopic quantum phenomenon. But the 1938 letter of Fritz London to *Nature* is the real birth of the theory of superfluidity, a very important breakthrough: quantum physics jumped from the microscopic world of atoms to the macroscopic world of visible matter like a litre of liquid helium.

Later on, Fritz London developed his ideas and some other physicists rejected his point of view, especially Lev Landau as we will see further down. But today, there is no doubt that London was careful, modest and perfectly right.

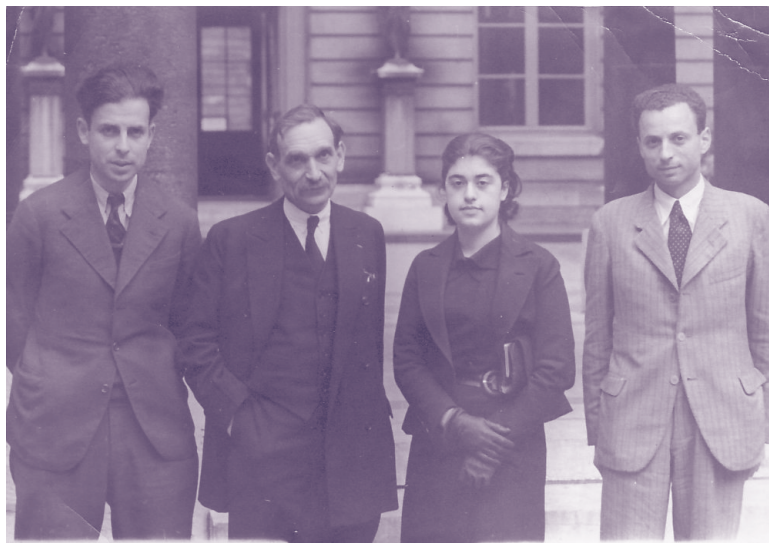


Fig. 5 At the *Collège de France* (Paris) in 1938. From left to right : Michel Magat, Edmond Bauer, Lydia Ochs (a student of the previous two) and Laszlo Tisza (personal collection of Laszlo Tisza).

5 Tisza and the two-fluid model

Fritz London was not working alone in Paris. Indeed, he had attracted a Hungarian refugee, Laszlo Tisza. Tisza had also worked on quantum chemistry but a few years later than Heitler and London, when quantum chemistry was developing: with Edward Teller they had built a theory for the methane molecule CH_4 . Tisza was facing the Hungarian Nazism. After one year in prison because he had a communist friend, he had been introduced by Edward Teller to Lev Landau who was building his famous school in Kharkov. Then, he spent two years with Landau before facing the strengthening of Stalinism in 1937. A few months before Landau was arrested by the NKVD, Beria's ancestor of the KGB, Tisza had to fly away again. Edward Teller and Leo Szilard³ recommended him to Fritz London who was looking for a close collaborator in Paris. London introduced Tisza to the same group of academics who had helped himself settling in Paris and, in September 1937, Laszlo Tisza arrived at the College de France, in the laboratory of Paul Langevin whose director was Edmond Bauer (fig. 5). The College de France and the Institut Henri Poincaré are close to each other in the centre of Paris so that London and Tisza started a fruitful collaboration on superfluidity.

When London explained to Tisza that the superfluidity of liquid helium could be a macroscopic phenomenon connected to the Bose-Einstein condensation, Tisza was quickly convinced and he tried to develop London's idea. In a

few days only, Tisza had another revolutionary idea. London had mainly considered static properties of superfluid helium and Tisza wanted to understand its strange hydrodynamics. He invented what is now known as the "two-fluid model". When thinking more about the condensation of atoms on a single quantum state, he realized that atoms should condense progressively as the temperature decreases below the λ -transition temperature. It is only at zero temperature that all atoms should group on a single state. At any intermediate temperature, only a fraction of the atoms should be really condensed. From this elementary view on the phenomenon at play, Tisza proposed that, in reality, superfluid helium had to be a kind of homogeneous mixture of two components, not one: a truly "superfluid component" with no viscosity and no entropy, plus a "normal component" made of non-condensed atoms, which was carrying entropy and responsible for dissipation consequently for some kind of viscosity. In the flow experiments by Kapitza and by Allen, the "normal component" should not flow through a very thin slit nor through a narrow capillary because it is viscous; on the contrary, the superfluid component could flow without any viscous resistance. From this assumption, he understood the difference between the early experiments in Toronto and the experiments in Cambridge and Moscow. He then predicted thermomechanical effects: forcing a superfluid to flow through a slit or through a micro-capillary should cool it down. Inversely, heating a superfluid on one side of a bottle that was partially closed on one side by a thin capillary should attract the superfluid component on the heated side of the bottle and increase the pressure there, so that a fountain

³ Both of these two Hungarian scientists played an important role in the development of the American atomic bomb.

should spring out. He had found a possible explanation of Allen's fountain effect. Soon, he proposed it to Fritz London. But London was very upset.

Tisza's proposal assumed that the components of his "two-fluid model" were able to move independently of each other and this was highly counterintuitive. London considered that Tisza was no longer respecting the necessary rationality of science and decided to stop collaborating with him. Of course, Tisza was deeply perturbed by London's reaction but he kept thinking that his two-fluid model allowed him to understand most of the experimental results. He then arrived at an important prediction: if the two components could move independently, then there should be not only acoustic waves in a superfluid but also "thermal waves" where the two components oscillate in opposite phase from each other. After having sent a short note to *Nature* on April 16th 1938, he wrote a communication in November 1938 for the *Comptes-Rendus* of the French Academy of Sciences, and another one in December. On October 1939, he sent another two articles to the *Journal de Physique*, where he proposed to take the existence of thermal waves in a superfluid as a crucial test of the validity of his model. By adopting this attitude, he was in obvious agreement with the definition of science by Karl Popper. But this test had to wait for several years before being made.

Indeed, the war between France and Germany had started on September 3rd 1939 and the "crucial test" was made in 1946 only. The answer was positive: a superfluid showed thermal waves in addition to sound waves but Tisza was not entirely right. Together with London, Tisza had initiated the theory of superfluidity but the reality was a little more complex as we shall see now.

6 London and Tisza escape from France

The war declaration forced London and Tisza to escape again, this time from France to the United States, and it was far from simple nor safe. London was already anxious in 1938 when he realized that antisemitism was growing in France and a war was coming. He thus tried to escape. After considering a possible position in Jerusalem, he accepted an offer from Duke University (North Carolina) where Paul Gross, a friend he had met in Paris, arranged to offer him a position of professor of theoretical chemistry. This invitation allowed him to obtain a visa for himself, his wife and their new born son Frank. Visa were difficult to obtain because the USA were severely restricting immigration. Then London borrowed some money from his brother Heinz and made reservations on the boat *Athenia* which was leaving France to Montreal via Liverpool on September 1st 1939. But, at the last limit, the London family was not accepted on this boat because they had German passports. Fortunately they

found another boat, the *Ile de France* sailing to New York via Southampton, on which they left on September 1st. On that day, the Wehrmacht invaded Poland. On September 3rd at 11 a.m. the United Kingdom declared war to Germany. At 5 p.m. France did the same. At 9 p.m. one of the German submarines destroyed the *Athenia*. It is miraculous that the London family was not on its board.

Tisza was less known and had no such offer for a position in the USA. He was still in France. Already in 1937, when leaving Hungary, he had applied for an American visa but he had not received any answer. In October 1939, together with Michel Magat, a friend chemist of Russian origin who was also in Langevin's laboratory, they entered the French Army in its foreign legion. However, Tisza stayed in his regiment for two months only because they discovered that he had serious heart problems. In a sense, Tisza was very fortunate because in June 1940, his regiment of foreign volunteers was destroyed by the Nazi tanks. However, he had entered the French army to prove his support to the nation that had welcomed him. He thus contributed to a collaboration with the military "Laboratory of Powders". This was perhaps also to protect himself against the anti-Semitic laws which were dangerously growing in France at that time. Jacques Hadamard, a famous mathematician from the *College de France* and his daughter Jacqueline who was working in Langevin's laboratory helped Laszlo Tisza and his wife Vera to escape from Paris just before it was invaded by the Wehrmacht. They succeeded in reaching Toulouse in the south of France but the situation there was not really safe either. Tisza had lost his CNRS position and had no rights to travel. Fortunately, they received their American visas in February 1941 and they succeeded in reaching Lisbon with other visas. After one month waiting for a boat, they left Europe and arrived in the USA at the end of March 1941. There, it was rather difficult to find a position but in September 1941 Laszlo Tisza entered the MIT as an instructor. In 1961 he was full professor at the same MIT. Both London's and Tisza's lives illustrate the difficulties refugees encountered in England and in France despite the help of local colleagues, also the difficulties they had to emigrate to the United States where the immigration was strictly controlled. In this last storm, the work of London and Tisza was interrupted.

7 Kapitza and Landau in Moscow

At the same time in USSR, research in Kapitza's Institute for Physical Problems did not stop but scientific life was far from quiet. In February 1937, Lev Landau had been forced to leave Kharkov by the development of Stalinism. He joined Kapitza in Moscow but in April 1938, when London and Tisza published their ideas in *Nature*, Landau wrote a leaflet to be distributed during the May 1st celebration where he

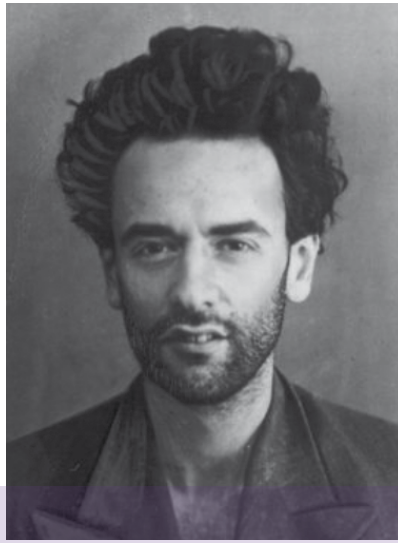


Fig. 6 Landau at the Lubianka prison in 1938 (archives of the KGB).

compared Stalin to Hitler and called people to get rid of him. Of course, this leaflet did not please the NKVD (the ancestor of the KGB) and Landau was immediately sent to the Lubianka prison where people were tortured and executed (fig. 6). Nearly one year later, in March 1939, Landau was hardly surviving there when Kapitza succeeded to liberate him after hard negotiations with Beria and Molotov. On April 6th 1939, in one of his letters to Molotov, head of the USSR government and close collaborator of Stalin, Kapitza justified the necessity of liberating Landau by writing:

"In my recent studies on liquid helium close to the absolute zero, I have succeeded in discovering a number of new phenomena which promise to shed light on one of the most puzzling areas of contemporary physics... I need theoretical help. In the Soviet Union, it is Landau who has the most perfect command on the theoretical field I need, but unfortunately he has been in custody for a whole year".

80 years later it seems difficult to understand how Molotov and Beria could appreciate the importance of superfluidity but, a few days later, Kapitza was summoned to the Lubianka and he obtained the liberation of Landau after engaging his own freedom as a guarantee that Landau would never cause any more trouble.

After returning to the Kapitza Institute, Landau quickly came back to physics and, in 1941, he simultaneously published a Russian version and an American version of an article entitled *"Theory of the superfluidity of Helium II"*. In this famous pair of articles, he proposed a theory of quantum liquids in which he derived a "two-fluid model" after severely criticizing the work of Tisza. There was no mention of Bose-Einstein condensation and he did not even mention London.

Landau's work was obviously more rigorous than Tisza's very short letter to *Nature*. But he ignored the other articles Tisza had written before leaving France. He had a different definition of the "normal component" introduced by Tisza: instead of being made of non-condensed atoms, he understood that it had to be made of collective excitations of the whole fluid. As a consequence, he also predicted the existence of thermal waves which he called "second sound", but without citing the prediction by Tisza three years before.

8 After the war

In July 1946, a large conference was organized in Cambridge on Low Temperature Physics. Both London and Landau were invited but Landau had no permission to leave USSR.

The opening talk was given by London with the title *"The present state of the theory of liquid helium"*. A few months before, the Russian physicist Vassili Peshkov had discovered in the Kapitza Institute the existence of the thermal waves or "second sound" that had been predicted by Tisza and by Landau. London was finally convinced that Tisza's intuition was right. But he was far from convinced by Landau's approach, which he considered as *"based on the shaky grounds of imaginary rotons"*. These rotons were a particular kind of collective excitations that Landau had indeed not introduced rigorously. Peshkov's results did not extend to very low temperature so that they looked in better agreement with Tisza's prediction than with Landau's one. As a consequence, London and Tisza had recovered their mutual understanding and support but the situation was not yet clear.

A few months later, Peshkov published new results in clear agreement with Landau's prediction. Landau increased his criticism of Tisza's. He also apologized for having missed Tisza's letters to the *Compte-Rendus*, but this is hard to believe since his very close collaborator Kapitza cited them at the same time.

As for the connection to the Bose-Einstein condensation, a more fundamental question, London and Tisza proposed to test its validity by studying the light isotope helium 3 instead of helium 4 which had been studied up to that time. Here again, I think of Karl Popper. Helium 3 is a product of the decay of tritium which was becoming progressively

available. Helium 3 atoms obey Fermi statistics while helium 4 atoms obey Bose statistics. Landau had developed his theory as if there were no difference between Bose and Fermi liquids. But the Bose-Einstein condensation is a property of Bose particles only, so that London and Tisza predicted that liquid helium 3 should not be superfluid. The test was made in 1949 by Osborne, Weinstock and Abraham and, this time, it proved that London and Tisza were right. As Lev Pitaevskii wrote in 1992, *"Landau was only one step from the very interesting subject of macroscopic quantum phenomena. But he never made this step. And there is no sense now to guess why..."* [6]. In 1973, Doug Osheroff, David Lee and Bob Richardson demonstrated that helium 3 has to form pairs to be superfluid, just like electrons in superconductors, and that it happens at a temperature thousand times lower than in helium 4.

In summary, London, Tisza and Landau had all found part of the truth but none of their original articles were entirely correct. As for the theoretical discovery of superfluidity, it would be unfair to attribute it to Landau only.

The whole story of the discovery of superfluidity illustrates that it is always difficult to identify the authors of a discovery at a time when science is becoming global at the scale of the whole world. This particular discovery also illustrates how scientists work sometimes. In the decade 1937-1947, they made fundamental breakthroughs in rather hard life conditions, as if some instability could be favourable to scientific creation.

References

- [1] S. Balibar *et al.*, *Phys. Rev. B*, 18 (1978) 3096, and the review by S. Balibar, *J. Low Temp. Phys.*, 185 (2016) 209, on "quantum evaporation".
- [2] A. Griffin, *"Superfluidity: three people, two papers, one prize"*, *Phys. World*, August 2008, p. 27.
- [3] S. Balibar, *"The Discovery of Superfluidity"*, *J. Low Temp. Phys.*, 146 (2007) 441; S. Balibar, *Un savant dans la tourmente*, to appear in October 2018.
- [4] P. E. Rubinin, *"The discovery of superfluidity. Letters and documents"*, *Phys. Usp.*, 40 (1997) 1249.
- [5] See for example: The Earl of Birkenhead *"The professor and the Prime Minister: The official life of Professor F.A. Lindemann, viscount Cherwell"* (Houghton Mifflin) 1962.
- [6] L. Pitaevskii, *"50 years of Landau's theory of superfluidity"*, *J. Low Temp. Phys.*, 87 (1992) 127.

Sébastien Balibar

Sébastien Balibar is Research Director at the Department of Physics of École Normale Supérieure (Paris), and member of the French Academy of Sciences. He is mainly recognized for his work on liquid and solid helium: quantum evaporation, roughening of crystal surfaces, cavitation, wetting, mechanical properties of quantum solids. For a large readership, he also wrote several books on recent scientific discoveries, the climate change and the daily life of scientists.