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# The forgotten brothers

**Stephen Blundell** tells of how Fritz London and his younger brother Heinz cracked the decades-long mystery of superconductivity, but wonders why their achievement is still overlooked today

In 1934 two brothers Fritz and Heinz London, both refugees from Nazi Germany, were working in an upstairs room in a rented house in Oxford. There they solved what was then one of the biggest problems in superconductivity, a phenomenon discovered 23 years earlier. The moment of discovery seems to have been sudden: Fritz shouted down to his wife “Edith, Edith come, we have it! Come up, we have it!” She later recalled, “I left everything, ran up and then the door was opened into my face. On my forehead I had a bruise for a week.” As Edith recovered from her knock, Fritz told her with delight “The equations are established – we have the solution. We can explain it.”

Though the discovery of what are now known as “the London equations” came in a dramatic flash of inspiration, the brothers’ ideas had been gestating for some time and their new intellectual framework would later mature through subsequent work by older brother Fritz. John Bardeen, who won his second Nobel prize in 1972 for co-developing the Bardeen–Cooper–Schrieffer (BCS) theory that provided a coherent framework for understanding superconductivity, regarded the achievement of the London brothers as pivotal. “By far the most important step towards understanding the phenomena”, Bardeen once wrote, “was the recogni-

tion by Fritz London that both superconductors and superfluid helium are macroscopic quantum systems.” Before then, quantum theory had only been thought to account for the properties of atoms and molecules at the microscopic level. As Bardeen explained, “It was Fritz London who first recognized that superconductivity and superfluidity result from manifestations of quantum phenomena on the scale of large objects.”

But despite Fritz’s leading role in the breakthrough that solved one of the knottiest conundrums of the early 20th century, he did not secure a permanent job at the University of Oxford once his temporary contract was up. Only two years later he was forced to up sticks and continue his postdoctoral wanderings. It might seem strange that such a bright spark was not snapped up, but even more surprising, perhaps, is the lack of recognition that the London brothers receive today. Like most institutions, Oxford has a culture of celebrating famous physicists of the past who have worked there, some of whom it has to be admitted have only had a rather tenuous connection with the place. But among the rows of photographs lining the walls of the Clarendon Laboratory, the London brothers are nowhere to be seen. How has this omission of recognition happened?

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### From Breslau to Oxford

Fritz London was born in 1900 in the German city of Breslau (now Wrocław, Poland) and nearly became a philosopher. However, he switched to physics and became immersed in the heady intellectual atmosphere of the 1920s that surrounded the new quantum theory. London's early career saw him travelling around Germany, taking positions with some of the great quantum pioneers of the time: Max Born in Göttingen; Arnold Sommerfeld in Munich; and Paul Ewald in Stuttgart. London worked on matrix mechanics and studied how the newly discovered operators of quantum mechanics behave under certain mathematical transformations, but he really made his name after moving again to Zurich in 1927. The lure of Zurich had been to work with Erwin Schrödinger, but almost immediately Schrödinger moved to Berlin and London teamed up with Walter Heitler instead. Together they produced the Heitler–London theory of molecular hydrogen – a bold and innovative step that essentially founded the discipline of quantum chemistry.

The following year London moved to Berlin, where he worked on intermolecular attraction and originated the concept of what are now known as London dispersion forces. He also succumbed to the interpersonal attraction of Edith Caspary, whom he married in 1929. By now the name “Fritz London” was becoming well known – he was fast gaining a reputation as a creative and productive theorist. However, with Hitler becoming German chancellor in 1933, the Nazis began a process of eliminating the many Jewish intellectuals from the country's academic system, putting both London and his younger brother Heinz at risk. Born in Bonn in 1907, Heinz had followed in his older brother's footsteps, studying physics, but became an experimentalist instead, obtaining his PhD under the famous low-temperature physicist Franz Simon.

A possible way out from the Nazi threat was provided by an unlikely source. Frederick Lindemann, later to become Winston Churchill's wartime chief scientific adviser and to finish his days as Viscount Cherwell, was then the head of the Clarendon Laboratory. Lindemann was half-German and had received his PhD in Berlin, so was well aware of the political situation in Germany. He decided to do what he could to provide a safe haven in Oxford for refugee scientists. His motives were not entirely altruistic, however: Oxford's physics department was then a bit of an intellectual backwater and this strategy would effect an instantaneous invigoration of its academic firepower in both theoretical and experimental terms. Later that year Lindemann persuaded the chemical company ICI to come up with funds to support his endeavour.

Lindemann initially lured both Schrödinger and Albert Einstein to Oxford, although Einstein quickly moved on to Princeton University in the US. Simon also came, bringing with him Heinz London as his assistant as well as Nicholas Kurti (later to be a pioneer of both microkelvin cryogenics and the application of physics to gastronomy). But Lindemann also wanted a theorist and admired Fritz London as a no-nonsense, practical sort of person who was able to work on down-to-earth problems. Thus both London brothers ended up in Oxford, Heinz sharing a rented house with his

### The London legacy begins



**Family affair** Left, Fritz London (1900–1954) and, right, his brother Heinz (1907–1970).

Some 23 years after the discovery of superconductivity, Fritz and Heinz London described how superconductors interact with electromagnetic fields. In doing so they introduced two equations that now bear their name. Their first equation is  $\mathbf{E} \propto d\mathbf{J}/dt$  and relates electric field,  $\mathbf{E}$ , to current density,  $\mathbf{J}$ , where  $t$  is time, and supersedes Ohm's law ( $\mathbf{E} = \rho\mathbf{J}$ , where  $\rho$  is the resistivity). Using Maxwell's equations it can be shown that this leads to  $\nabla^2(d\mathbf{B}/dt) = (d\mathbf{B}/dt)/\lambda^2$ , which predicts blocking out or “screening” of time-varying magnetic fields on a length scale  $\lambda$ . This is enough to explain the Meissner effect, which shows that the magnetic field,  $\mathbf{B}$ , itself is screened.

In 1935 the London brothers argued that a more fundamental relation is given by their second equation,  $\nabla \times \mathbf{J} \propto -\mathbf{B}$ , which, using Maxwell's equations, gives  $\nabla^2\mathbf{B} = \mathbf{B}/\lambda^2$ . This predicts screening of the magnetic field itself, so that an external magnetic field can only penetrate into the surface of a superconductor over a length scale  $\lambda$ , which is now called the London penetration depth. Fritz London later realized that the locking of all carriers into a single momentum state yields the relation  $\mathbf{J} = -(nq^2/m)\mathbf{A}$ , where there are  $n$  carriers per unit volume, each with mass  $m$  and charge  $q$ . This equation linking current density and the magnetic vector potential,  $\mathbf{A}$ , is probably the best summary of the London theory.

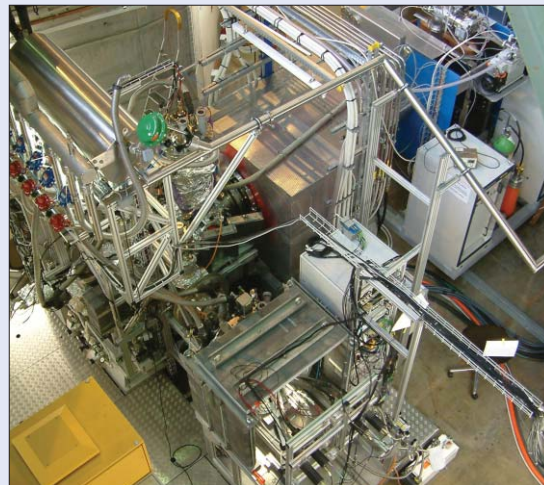
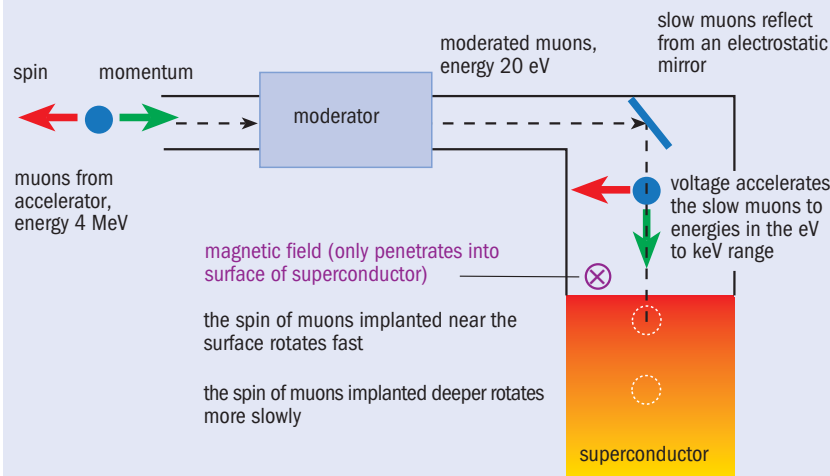
brother and sister-in-law. Fritz was the superior theorist but Heinz had deep insight into, and a great love for, thermodynamics, something that he had picked up from Simon. He frequently quipped “For the second law, I will burn at the stake.” With Simon's arrival in Oxford, and the installation there of the first helium liquefier in Britain, experimental research began on low-temperature physics, leading Fritz London to work on superconductivity.

### The quest to understand superconductivity

The discovery of superconductivity in April 1911 by Heike Kamerlingh Onnes and Gilles Holst was the inevitable consequence of Onnes devoting many years to the development of the cryogenic technology needed to achieve low temperatures. With Onnes's laboratory in Leiden being the first to liquefy helium came the first chance to explore how materials behave in such extreme low-temperature conditions. The disappearance of electrical resistance in a sample of mercury was an unexpected shock, but in retrospect it was an inevitable consequence of having developed a far-reaching new technology that opened up an unexplored world.

But nobody knew how this new effect worked. For decades theorists tried and failed to come up with an

## 1 All in a spin



Elvezio Morenzoni, PSI

The London penetration depth, which is the distance a magnetic field can penetrate into a superconductor, can be inferred using various experimental techniques. Since the 1990s, Elvezio Morenzoni and co-workers at the Paul Scherrer Institute in Switzerland have developed a method of measuring it directly. They use spin-polarized positive muons as a probe. These particles are slowed or “moderated” to a low energy and then reaccelerated into the surface of a superconductor by applying a voltage to it. By varying this voltage, the muons can be implanted at different depths. A magnetic field is then applied and the spin of the muon precesses at a rate that depends on the field it experiences. Measuring this rotational speed of the spin of the muon yields the magnetic field inside the superconductor at different depths, and hence the London penetration depth can be extracted.

explanation. Felix Bloch is remembered for his eponymous theorem about waves in periodic potentials, but his failure to make progress with understanding superconductivity reduced him to formulate a tongue-in-cheek statement that also became known at the time as Bloch’s theorem: “the only theorem about superconductivity that can be proved is that any theory of superconductivity is refutable” or, more succinctly, “superconductivity is impossible”.

The crucial clue came from the famous 1933 experiment of Walther Meissner and Robert Ochsenfeld. They showed that a superconductor cooled to below its transition temperature in an applied magnetic field suddenly expels that magnetic field. In this “Meissner effect”, surface superconducting electrical currents (supercurrents) flow around the superconductor in such a way as to shield the interior from the applied magnetic field. These circulating supercurrents oppose the applied magnetic field, so that deep within the superconductor the magnetic field is close to zero – an effect known as perfect diamagnetism. Fritz London realized that this perfect diamagnetism is even more central to the behaviour of a superconductor than perfect conductivity. Until then perfect conductivity had been thought of as the superconductor’s defining quality – hence the name – but London realized that it is more of a by-product. While others had been trying to figure out how to formulate a new Ohm’s law for a superconductor, in other words to find a relationship between electric current and electric field, London saw that what was needed was a new relation between electric current and magnetic field.

Existing theories had postulated some sort of acceleration equation: an electric field might not drive a current (as it does in a conventional metal) but it might cause one to accelerate. The perfect conductivity in a superconductor meant that there could be no electric field, but this absence of an electric field could be con-

sistent with an already accelerated current of carriers. However, the equations that described this situation only led to a screening of time-varying magnetic fields and not time-independent ones, as evidently screened in the Meissner–Ochsenfeld experiment, and so did not account for the observations.

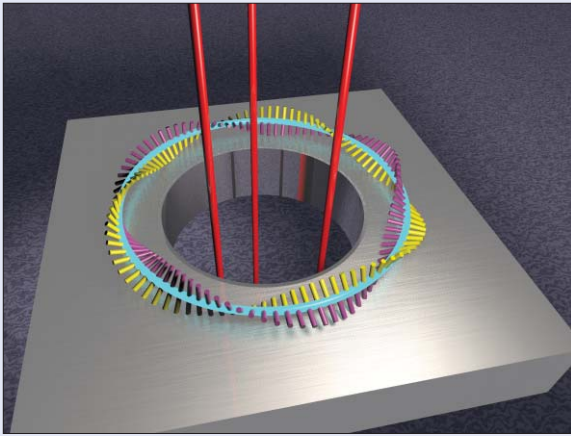
The London brothers instead insisted that the fundamental principle of superconductivity is the expulsion of magnetic fields. It was their conviction in this line of thought that led to their 1934 eureka moment – the one that caused Edith London’s bruised forehead. They postulated an equation that links the magnetic field to the electric current density and produces the required screening of static magnetic fields and hence the Meissner effect (see box on page 27). This equation and the brothers’ modified version of an acceleration equation became known as the London equations, which they published in 1935 (*Proc. R. Soc. A* **149** 71). Their theory also predicted a length scale over which a magnetic field can penetrate through the surface of a superconductor, which became known as the London penetration depth (figure 1).

#### When the money runs out

In formulating their theory, the London brothers made the most significant progress in our understanding of superconductors in the first half of the 20th century. However, their situation at Oxford was precarious. Their 1935 paper contains a fulsome acknowledgment to “Professor F A Lindemann, FRS, for his kind hospitality at the Clarendon Laboratory” and also to “Imperial Chemical Industries whose generous assistance to one of us has enabled us to undertake this work”. However, the hospitality and generosity were coming to an end.

By 1936 the ICI money that had funded the refugee scientists had dried up and Lindemann could not find funds to offer positions to all of them: he had to make

## 2 Magnetic flux quanta



The magnetic flux through a hole in a superconductor is related to the supercurrent around the inside of the hole. Because the supercurrent (light blue) is phase coherent, the phase of the wavefunction must wind an integer number of times around the loop (shown schematically by yellow and purple rods), which leads to the magnetic flux (red) being quantized. The number of times the wavefunction winds round the loop – here three – is equal to the number of magnetic flux quanta through the loop.

a choice. Heinz was in a junior position without any expectation of remaining at Oxford, and so took an appointment at the University of Bristol, but Fritz entertained hopes of staying on. Schrödinger was a big name and was clearly a high priority for Lindemann to keep, though Schrödinger subsequently left anyway and settled in Dublin. Lindemann also wanted to retain the famous Simon. Fritz London, who had apparently only produced some obscure theoretical work with his brother, which few at Oxford really understood, was told that his contract was at an end.

Fritz therefore accepted an offer of another temporary research position in Paris, where he stayed for three years, eventually leaving for a permanent academic position at Duke University in North Carolina. Fritz and his wife departed from France in September 1939, though because of their German passports they were not permitted to sail on the ship they had planned to board and they were forced to take a later one. This was just as well, as German U-boats torpedoed the earlier ship, with great loss of life.

### Macroscopic quantum coherence

Through work begun in Oxford and furthered in Paris, Fritz London grasped that superconductivity is an example of quantum coherence writ large – not on the scale of a single atom a fraction of a nanometre across, but on the scale of a piece of superconducting wire centimetres across. He coined the phrase *macroscopic quantum phenomenon* to categorize superconductivity: a macroscopic sample of superconductor behaves like a giant atom.

In a normal metal, electrons have the freedom to occupy many different quantum states, but London realized that the carriers in a superconductor are far more constrained. As London put it: “If the various supercurrents really were to correspond to a continuum of different quantum states, it would seem extremely

hard to understand how a supercurrent could resist so many temptations to dissipate into other states.” By locking all the carriers into a single quantum state the supercurrent is fixed to a single value and has no freedom to do anything else. This means that a supercurrent flowing around a loop of wire keeps going on and on, endlessly circulating without dissipation.

London noticed that this behaviour is reminiscent of the orbits of electrons around an atom: the energy and angular momentum of an electron in an atom are restricted to certain quantized values, because the electronic wavefunction is coherent around the atom. In 1948, still at Duke, he deduced that because the wavefunction in a superconductor is coherent, something similar must occur. If one takes a loop of superconducting wire with a current flowing endlessly round it, London showed that the magnetic flux penetrating the loop should be quantized to certain fixed values (figure 2). A supercurrent travelling in a loop produces a magnetic field that is a precise signature of that supercurrent, and the quantization of magnetic flux is intimately related to the nailing down of that supercurrent to a single quantum state. London calculated that the quantum of magnetic flux would be exceedingly tiny and thus impossible to observe with techniques available at the time. In fact, it was not until 1961, four years after London’s death in 1957, that magnetic flux quantization was experimentally observed by Robert Doll and Martin Näbauer, and, independently, by Bascom S Deaver Jr and William Fairbank.

By that time, the remarkable achievement of Bardeen, Robert Cooper and Leon Schrieffer had provided the world with a wonderfully complete theory of superconductivity that explained most of the properties that had been measured so far. The edifice of BCS theory was built squarely on the foundations provided by Fritz London and his concept of a coherent and rigid wavefunction. London’s vision of macroscopic quantum coherence, where the subtle absurdities of quantum mechanics are writ large, is now a firmly established part of physics, but is no less wonderful or surprising for that.

Bardeen demonstrated his respect for Fritz London’s work by using his cut of the 1972 Nobel prize (he also shared the 1956 prize for discovering the transistor) to fund the Fritz London memorial prize, which recognizes outstanding contributions to low-temperature physics. Duke University has a chair named in his honour, and Fritz London’s life has been recorded in Kostas Gavroglu’s superb 1995 biography. But what is striking is how little known the London brothers are, and in particular the lack of recognition they receive today at the very institution where they came up with those paradigm-changing equations. Perhaps the reason is that Lindemann, who was inordinately proud of his achievement in getting various Jewish scientists out of Germany in the 1930s, did not want to be reminded of the one he was forced to get rid of. In this centenary year of superconductivity I am ensuring that photographs of the London brothers will be hung in the Clarendon Laboratory, and am enthusiastic about publicizing their remarkable contribution to making quantum mechanics move out of the microscopic world of atoms and into our own. ■

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