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Superconductors and Superfluids
– Matter Wave Analogs of the LASER

Superconductors and superfluids are fascinating examples of so-called *quantum fluids*. A *quantum fluid*, as opposed to a *classical fluid*, is a liquid state where the *wave-like* nature of the particles constituting the liquid has emerged. Every particle has associated with it a so-called thermal de Broglie wavelength which increases upon lowering the temperature, whence the wave-like character inevitably emerges. As this wavelength increases and becomes comparable to the interparticle distance, the fluid changes character from being a classical fluid to a quantum fluid. When the wave-like nature of particles is important, it requires the use *quantum mechanics or wave-mechanics* to describe them. In quantum mechanics, we describe a system of particles by a wave function that in itself does not have any immediate physical interpretation. However, it can be used to *compute* observables. It has the strange property of being complex in the mathematical sense, i.e. it has a real and imaginary part. Alternatively, we may describe this function has having a length and a direction in a complex plane. This sounds abstract, but the very existence of superconductors and superfluids is a direct manifestation of an astonishing self-organization in the *direction* of this unworldly-sounding wave function. The direction, or the phase, of the wave function becomes the same throughout the system when a fluid becomes superconducting or superfluid. It is very much like phase-ordering in LASERs, which are phase-coherent light waves; superconductors and superfluids are macroscopically phase-coherent matter waves.

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The fluid in a metal that becomes superconducting is a fluid of electrons that flow in a background matrix of an ionic solid which may or may not have good crystalline order. They are charged elementary particles with the additional property of having spin, i.e. a little magnetic moment attached to them. The spin of an electron is as small as it can possibly get without being zero, namely ½, measured in units of Planck's constant, the natural unit for spin. A superfluid is comprised of atoms without charge, but which may or may not have spin. It is important to distinguish whether these atoms have integer (including 0) or half-integer valued spin.

In 1908, Heike Kammerling Onnes succeeded in liquefying helium for the first time. At ambient pressure, helium boils/condenses at 4.22 K, only about 4 degrees above the absolute zero of temperature (Fossheim 2004). A meticulous and continuous effort over many years led to the determination of the so-called isotherms of helium, and this was a key ingredient in achieving success. To quote the Swedish Academy, which awarded

Kammerling Onnes the Nobel Prize in 1913: "The attainment of these low temperatures is of the greatest importance to physics research, for at these temperatures both the properties of the substances and also the course followed by physical phenomena, are generally quite different from those at our normal and higher temperatures, and a knowledge of these changes is of fundamental importance in answering many of the questions of modern physics." These were truly prophetic words, in view of what was to come.

An important issue in physics around 1910, was what happened to the electrical resistivity of conducting materials as they were cooled down. Specifically, two possibilities were suggested, namely the gradual vanishing of resistivity as the temperature went to zero, alternatively that a residual resistivity would remain. It was natural to use helium-cooling of metals to investigate this issue. Mercury stood out as a prime candidate for this investigation, since it could be made extremely pure by repeated distillation. This is important, since resistivity at low temperatures is mainly determined by impurity scattering. Kammerlingh-Onnes therefore set out to investigate mercury's low-temperature transport properties. He found, to everyone's amazement, a sudden drop in the resistivity at 4.1 K, at which point the resistivity became immeasurably low. This phenomenon was called 'superconductivity'. The spectacular and sudden loss of electrical resistivity is basically the biproduct of a radical change, a phase transition, taking place in the liquid of conduction electrons in the metal. The sharply defined temperature at which the phenomenon takes place is called the critical temperature.

In 1933, it was found that in a superconductor, an externally applied magnetic field would be expelled from the specimen. If a too strong magnetic field was applied, superconductivity would break down. This is called the Meissner effect. Superconductors that completely expel magnetic fields and then suddenly break down completely for too large magnetic fields are called Type I superconductors. The expulsion of magnetic flux would not take place in a *perfect* conductor of free electrons, showing that 'superconductivity' is more than just 'perfect conductivity'. Based on this, Fritz London came up with the London phenomenological theory of superconductors, in which the current inside a superconductor was assumed to be proportional, not to the electric field as in an ordinary metal, but proportional to a quantity called the vector potential, whose rotation gives the magnetic field. This explains the Meissner effect. London was the first to suggest that the superconducting state was a state in which a metal had taken up a state in which the wave function of the system had developed 'rigidity'. This is essentially right on the mark! However, it remained a mystery what the wave function in question actually described. That mystery would only be solved much later (see below).

In 1938, Pjotr Kapitza found that liquid helium suddenly looses its viscosity when cooled down to 2.17 K (Khalatnikov 1989, Annett 2004). The loss of viscosity is the counterpart in helium to the loss of electrical resistivity in a metal. This loss of viscosity was called superfluidity. There is a fascinating analog of the Meissner effect in helium. Recall that a magnetic field couples to matter in two ways, either via the spin of a particle or via its charge. It is the coupling to charge which is important for the Meissner effect. However, helium is a noble gas made up of neutral (uncharged) and spinless atoms! The analog is as follows: Suppose you rotate a bucket of helium. The superfluid liquid in the bucket remains irrotational if the rotational frequency is not too large. When it exceeds some critical value, the liquid remains irrotational except along certain lines parallel to the rotation vector, where specific quanta of rotation appear. These lines are arranged in a hexagonal pattern in the plane perpendicular to the lines, and are lines of quantized vorticity, or vortex lines.

Such vortex lines were later *predicted* to occur, even in superconductors subjected to an external magnetic field by Alexeii Abrikosov. It is a rare example of a correct, non-trivial *prediction* in the theory of quantum fluids (Fossheim 2004). The magnetic field in a superconductor plays an analogous role to rotation in helium. Abrikosov was describing what is called Type-II superconductors, which exhibit a complete expulsion of magnetic fields at low enough fields, followed by a partial expulsion of magnetic fields at intermediate fields, and finally a complete breakdown of superconductivity at high enough fields. For many years after the publication of this seminal work (which was awarded the Nobel Prize in Physics 2003), it was controversial whether such flux lines existed in superconductors. However, by depositing iron filaments on top of a superconductor in a magnetic field, it is possible to directly observe vortex lines with the naked eye. They are extremely important in determining the transport properties of Type-II superconductors.

The explanation for superconductivity in metals such as mercury, tin, lead, and aluminum, came in 1957 with the famous Bardeen-Cooper-Schrieffer (BCS) theory. They realized in a brilliant flash of insight that there was a tiny piece of *attractive* interaction between electrons, mediated by the lattice of ions that the electrons move through, which was able to overcome the large Coulomb *repulsion* between electrons in a metal, in such a way as to stabilize so-called Cooper electron pairs. This is the genesis of superconductivity. Compared with non-interacting electrons in a three-dimensional metal, even a strong repulsive interaction can be ignored. On the other hand, any tiny amount of attractive interaction is a completely singular addition to the free electron gas. After 46 years of searching, Bardeen, Cooper, and Schrieffer succeeded in correctly identifying the needle in the haystack required for superconductivity. They identified the wave function of a Cooper pair as the mysterious London wave function. 2007 marks the 50th anniversary of this major landmark of human intellectual achievement.

The explanation for superfluidity in helium as observed by Kapitza is quite different from the BCS theory, and in some senses simpler. The helium isotope in Kapitza's fluid has two protons and two neutrons in the nucleus, and is a boson. Bosons have the intrinsic property of preferring to *macroscopically* occupy one and the same single-particle state at low temperatures. This is called Bose-Einstein condensation. (Fermions such as electrons are quite the opposite. Two of them cannot possibly occupy the same single-particle state). Superfluidity in bosonic helium is simply Bose-Einstein condensation in a strongly interacting bosonic fluid. However, helium has another isotope with two protons and one neutron, which is a fermion. Superfluidity in this liquid, now in the milli-Kelvin regime, was discovered in 1972. The discovery was awarded the Nobel Prize in 1997. The theory for this is much more elaborate than for bosonic helium. Since this fluid is comprised of fermions, it is again a matter of making Cooper pairs by some interaction (which has to be different in origin from the lattice-mediated interactions for the metals described above). The wave function for these Cooper pairs turns out to be a monster with no fewer than nine complex components, compared with one in the BCS theory of superconductivity. The phase coherence in such rich and complex matter waves will continue to intrigue researchers for many decades to come.

We cannot end without mentioning high-temperature superconductivity, discovered in cuprate oxides in 1987 by Alex Mueller and Karl Bednorz. This was one of the most important scientific discoveries of the 20th century. It is a great paradox that these materials, the best superconductors the world has ever seen, are also the worst metals! Even the normal metallic state of these wonderful compounds is enigmatic, and the quest for a theory of this phenomenon is perhaps the deepest problem in physics today. Finally, we mention predictions of novel quantum fluids that may be both superconductors and superfluids (Babaev 2004). This happens to be a possibility in the most abundant element in the universe, namely hydrogen, but only under extreme conditions. Researchers are working hard to realize this new state of matter.

Research on these fascinating quantum fluids over the last century has pushed the frontiers of science forward. The no less than 13 Nobel Prizes in physics that have been awarded to research on superconductors and superfluids bear witness to that.

References

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