International Particle Physics Outreach Group

Working group
OUTREACH of APPLICATION FOR SOCIETY
May, 2024

Superconductivity – quantum mechanics at work

Just a dream or already reality?

If you have ever seen a picture of a levitating train like the one in Shanghai, then you have seen an example of superconductivity at work.

Fig. 1) A maglev train coming out, Pudong International Airport, Shanghai, Foto Alex Needham

What is a superconductor?

A superconductor is a perfect conductor that conducts electricity without resistance. This means that no energy is converted into heat, and a current flowing through the material does not change in magnitude.
In normal metallic conductors, resistance decreases with temperature and the resistance disappears at the temperature of absolute zero, 0 degrees Kelvin or -273º Celsius.
Superconductivity was accidentally discovered in 1911 by the Dutch physicist Heike Kamerlingh Onnes, who was experimenting with the liquefaction of gases at very low temperatures. He found an amazing effect in mercury where the electric resistance disappeared at a very low temperature of 4.2 K. This temperature is called the transition temperature.

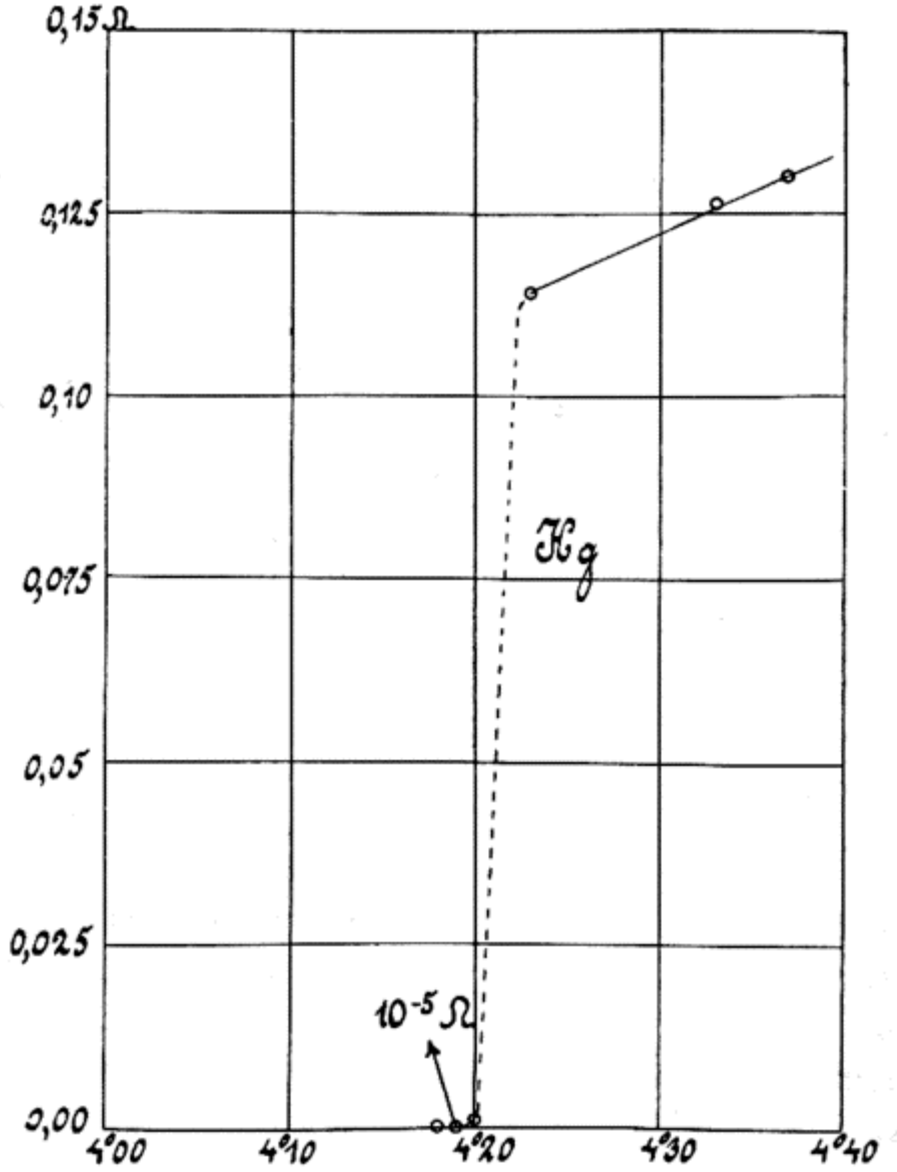

Fig. 2) This hand-made figure from the original publication of H. K. Onnes, (Commun. Phys. Lab.12,120, (1911)) shows the measured resistance as a function of the measured temperature in Kelvin. Note the drop in the resistance to 10-5 Ω at the 4.2 K transition.

A superconductor has a second physical property: superconductors respond to an external magnetic field by tending to repel it, forming a perfect diamagnet, – the superconductor "becomes" an opposite magnet and feels a repulsion force. This property gives rise to the surprising effect of levitation .

Fig. 3) Magnetic levitation of a superconductor (Foto: Science Pavilion UZH)

The quest is on ...
For more than 100 years, researchers have been working to find superconducting materials at higher temperatures because, although liquid helium is an excellent cooling medium, it has two problems: 1) It is quite expensive, and it requires sophisticated technologies to keep a system at liquid helium temperature. 2) It is a non-renewable and limited resource on earth (read more) – although it is the second most abundant element.

The breakthrough

In the decades following the discovery, scientists found materials that became superconducting at higher temperatures. However, all the superconductors that were found until 1986 had very low transition temperatures, making them dependent on a cooling system with liquid helium. In the 1980’s two researchers entered the field and revolutionised research on superconductivity: K. Alex Müller and J. Georg Bednorz, who at the time were working at the IBM Research Laboratory in Rüschlikon, near Zurich on ceramic materials, so called perovskites, with a focus on their chemical binding, ferroelectric properties, and later on phase transitions. In early 1983 K. Alex Müller, also professor at the University of Zurich, became interested in superconductors and started research on oxide ceramics. The breakthrough came in 1986 with the discovery of high-temperature superconductors (HTS), for which the two scientists were awarded the Nobel Prize in Physics a year later in 1987.
In the following years, many more other superconducting ceramics were found with transition temperatures below the temperature where nitrogen becomes liquid (-196º), thus avoiding the problem of cooling with helium. The technical application of these new materials is still limited as the ceramics are usually quite brittle.
Watch this video on the breakthrough-discovery of high-temperature superconductivity.

Fig. 4) K. Alex Müller and J. Georg Bednorz. Image Archive the ETH Library.

Connection to IPPOG:
Katharina Müller, the Swiss representative of IPPOG had the privilege to work on high temperature superconductivity at the University of Zurich at the time of the big breakthrough in the late 1980s. She remembers extremely lively discussions in the labs and during seminars.

What is it good for?

Many technological applications benefit from superconductivity. Some are already in use, others are still in development. Here a few examples:

- Strong magnetic fields
  electric currents generate magnetic fields. In order to produce strong magnetic fields as needed for example for magnetic resonance imaging (MRI) the currents exceed 10'000 A, making conventional cables of no use. Superconducting magnets are also used in the Large Hadron Collider at CERN to create the 8 Tesla magnetic field needed for keeping the 7 TeV protons on a circular path.
- Energy storage
  Superconducting Magnetic Energy Storage (SMES) is a technology that stores electricity in a magnetic field with very high efficiency.
- Long-distance energy transfer
  Electric energy can be transported without losses and without the need for high-voltage DC overhead lines, which are currently the cheapest option. For example, superconducting cables are currently used for the power distribution in some cities.
- Superconducting Quantum Interference Device (SQUID)
  SQUIDs are very sensitive devices used to measure extremely small magnetic fields, such as neural activity in the brain.
- Levitating trains
  Some levitating train concepts use superconducting magnets to elevate the trains by about 10 cm. Elevated trains can reach much higher speeds because friction is greatly reduced.

Videos K. A Müller

- Video from Müller's superconductor to Keller's leviating train
  https://www.youtube.com/watch?v=r4eaP2Ks0aQ
- Nice video with Müller http://www.vega.org.uk/video/programme/33
- 1987 K. Alex Müller at the American Physical Society
  https://www.youtube.com/watch?v=1IJoikdY5dA
- Some Remarks on the Symmetry of the Superconducting Wavefunction in the Cuprates
  https://mediatheque.lindau-nobel.org/recordings/31342/some-remarks-on-the-symmetry-of-the-superconducting-wavefunction-in-the-cuprates-2004
- https://videos.cern.ch/record/43769/embed
- https://www.flickr.com/photos/ibm_research_zurich/4173353017
  IBM Nobel laureates Georg Bednorz and K. Alex Müller discuss and demonstrate their prize winning work in superconductivity in 1989

Easy to digest text
https://home.cern/science/engineering/superconductivity

More advanced text
BCS Theory https://en.wikipedia.org/wiki/BCS_theory
Original paper describing the theory behind superconductivity
https://journals.aps.org/pr/abstract/10.1103/PhysRev.108.1175