Feature Article

100 years of Superconductivity

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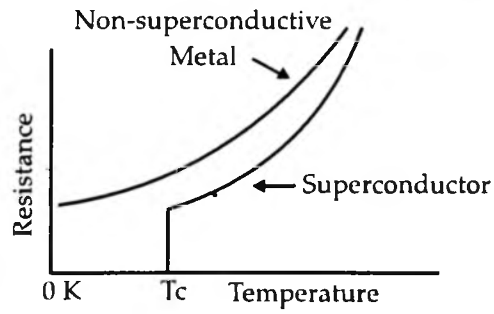
Abstract:

100 years of the discovery of superconductivity was celebrated in 2011. The complete absence of electrical resistance in some materials below a critical temperature Tc continues to fascinate the scientific community even today. Though the above phenomenon in metals is one of the best understood phenomenon in solid-state physics, superconductivity in the cuprates discovered in 1986 is far from reaching a consensus. Superconductivity has become a multi-billion dollar industry, with applications in medical imaging, cell phone filters, electrical motors, power transmission transportation, magnetic sensing etc. In this article, we briefly describe some of the important landmarks in the last 100 years of superconductivity. Some of the important applications of superconductivity are also discussed below.

Superconductivity - the disappearance of resistance in certain materials - is one of nature's strange phenomena that celebrated its 100th anniversary of its discovery in 2011. Metallic wires have electric resistance that uses up energy as the current flows through the wire, turning it into waste heat. Superconductors are materials with no electric resistance at all: an electric current can flow through a superconductor without losing any energy. By early 1911 it was well known that the electric resistance in a metal decreased with temperature. However, exactly what would happen approaching absolute zero was debated. Lord Kelvin believed that the flow of electrons which seemingly improved with decreasing temperature (as the lower resistance indicated) might actually stop altogether, the electrons becoming frozen in space. The resistance at absolute zero would be infinitely high. Others assumed that the decrease in resistance would continue in an orderly manner, ultimately reaching zero at the zero temperature point. Finally in 1911, Kamerlingh Onnes and



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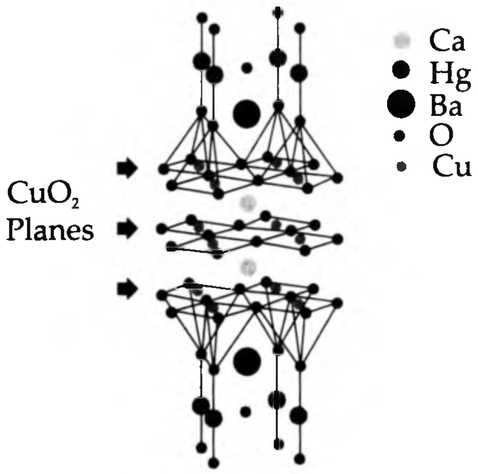


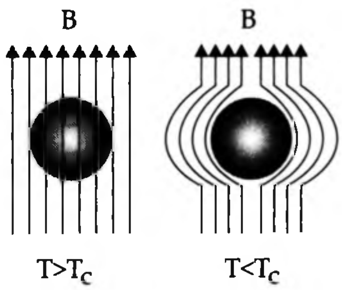
his collaborator Gilles Holst in a laboratory at Leiden, Netherlands observed the resistance of mercury to fall by a factor of at least 1010 at a temperature of about 4.2K for the first time [1,2] . The liquefication of He in the laboratory of Onnes gave him the possibility of refrigeration to very low temperatures. He chose Hg as it could be easily purified. Soon it became clear that the resistance of some metals including mercury really does fall to zero at a particular temperature, known as critical temperature Tc. Any current introduced into the superconductor loop will continue to flow indefinitely. The zero resistance is not the only signature of superconductors, Meissner effect leading to perfect diamagnetism is the second Hallmark of these materials [3].

The problem of these classical superconductors remained at the forefront of theoretical physics

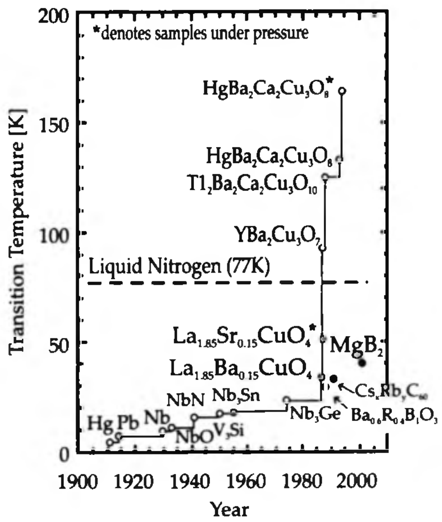
until 1957, when a microscopic theory was proposed by Bardeen, Cooper and Schrieffer (BCS) from UIUC, Illinois [4]. Along the way most of the great theoretical physicists including Bohr, Heisenberg, Pauli, Bethe, Bloch, Sommerfeld, Yang and Feynmann worked on the problem, yet the solution came only after nearly 50 years from its discovery. The insurgence of the quantum mechanics in the thirties brought new hope to the pioneers of this field but as time went on various workers became frustrated leading Felix Bloch to comment "every theory of superconductivity can be disproved". One of the key ideas of the BCS theory is the pairing of electrons brought about by a weak interaction. Despite the Coulomb repulsion between the electrons, they are paired due to the interaction of electrons with the crystal lattice. Interestingly the pairs of electrons are condensed into the same quantum state like the atoms in the Bose-Einstein Condensation. Following the success of the BCS theory, the next landmark was the prediction, in 1962, by Brian Josephson at Cambridge University in the UK that a current could tunnel across two superconductors separated by a thin insulating or normal metal barrier [5]. This came to be known as the Josephson effect and resulted in the development of superconducting quantum interference device (SQUID) which can measure minute levels of magnetic field. The highest Tc in metals was found in Nb (9.25 K). After 1957, BCS theory paved a path for new research in finding new superconductors. However, new superconductors were not discovered in many years to follow which was very well supported by good theoretical reasons.

Discovery of high-Tc superconductivity in cuprates

In 1986, after a long time of silence the community greeted the announcement of superconductivity at 35 K in the lanthanum barium copper oxide (La-Ba-Cu-O) system by Georg Bednorz and Alex Müller of IBM-Zurich in September 1986 [6]. They themselves could not believe the results and only after several repetitions of their measurement that they actually submitted a paper to Zeitschrift für Physik on April 17, 1986. It was a historical moment in the era of science. It was a big jump in the value of the critical temperature. This led



to a new series of compounds, more specifically doped ceramics, which came to be known as High Temperature Superconductors. The original paper reported zero resistance but no Meissner effect. This provoked skepticism because the literature is full of claims of superconductivity even upto values which is close to room temperature. The zero resistance was quickly followed by a confirmation of the Meissner effect in Europhyiscs letters. Laboratories all around tried to reproduce these results and take a forefront in this area. The critical temperature increased very rapidly. The



new period that began in 1986 might be called the copper oxide era because so far, the presence of copper and oxygen has with rare exceptions been found essential for Tc above 40 K. Soon after the discovery of this superconducting La-Ba-Cu-O by Müller and Bednorz, in 1987 Paul Chu of University of Houston in collaboration with Mang-Kang Wu [7] of the University of Alabama discovered a new class of superconducting materials, known as ``123" class, exemplified by YBa2Cu3O7-δ ("YBCO") published in Physical Review Letters which possessed a Tc of over 90K. [In this structure, the Y (yttrium) can be replaced by many rare earth elements, e.g., La, Nd, Sm, Eu, Gd, Ho, Er and Lu, with similarly high Tc.] They observed that the applied pressure elevates Tc in the La-based cuprates and thus reasoned that rare earth atoms with a smaller ionic radius may exert a desired chemical pressure in the cuprate lattice. Shortly thereafter, escalating optimism was encouraged by the discoveries of Tc =110 K in the ``BSCCO" system (mixed oxide of bismuth, strontium, calcium and copper) [8], Tc=125 K in the ``TBCCO" [9] system (mixed oxide of thallium, barium, calcium and copper) and Tc=133 K in the ``Hg-1223" systems [10,11]. Application of pressure [12,13] to Hg-1223 pushed the current record to Tc=164 K) halfway to room temperature. A dramatic increase in Tc has been observed since 1986. It is interesting to observe that mercury was the first known superconductor and 100 years later, mercury compounds are the best. There appears to be no end in sight and perhaps some day there will be a room temperature superconductor. More importantly they did not need to be cooled to very low temperatures to become superconductors. These high temperature superconductors opened the door to applications that can work without liquid Helium and can instead use liquid nitrogen which boils at 77 K. Liquid nitrogen costs under 10 cents per litre, less than 1/20 th of the price of liquid helium. All the high temperature superconducting ceramics discovered so far contain copper, but their constituents can be varied. Values of Tc in excess of the boiling temperature of liquid nitrogen immediately implicated high Tc cuprates as the promising candidates for technological applications of superconductivity. So we see that the critical temperature reached nearly four times the limit considered in the conventional superconductors and the most promising are those containing an oxide of copper, known as cuprates.

The cuprates consist of one or more CuO2 planes in their structure separated by layers of other atoms (Ba, La...). These planes are the location of the superconducting carriers, and they must be created by varying the content of oxygen or one of the other constituents – "doping" the material. We can see how this works most simply in the first high temperature superconductor, which was La2CuO4 doped with Ba to give La2–xBaxCuO4 (x~0.15 gives the highest Tc).compounds, lanthanum forms. So we have convenient, inexpensive superconductors at hand. On March 10, 1987 the New York Times came up saying "If you wanted to dream further, you could see the day when instead of cars with wheels you have levitating cars". The possibility of the room temperature superconductors was envisioned. With all this publicity the number of people engaging to work on new superconducting materials started exploding. For scientists it was an opportunity of a lifetime, a chance to be a part of a major technological breakthrough. With this discovery hope emerged that many of the useful devices incorporating superconductivity that have been conceived over the years would now become economically viable. Since 1987, there has been a phenomenal growth in scientific literature devoted to the subject of superconductivity. It increased so rapidly that new journals devoted exclusively to the subject were formed. However, these new materials are far from being understood theoretically due to highly anomalous nature of these doped materials. Moreover, BCS theory is descriptive and qualitative, not quantitative and hence fails to point out the nature of materials that could yield superconductivity. On the experimental side, the maximum Tc has been stuck at about halfway to room temperature since the early 90s.

Transmission systems; Cold technology

Many uses have been suggested for superconductivity. Perhaps the most obvious is for carrying electrical power from place to place. Electricity is usually generated in large power stations, and transmitted along power lines to consumers who may be hundreds of kilometers away. Typically, resistive heating in the metal wires of the transmission lines consumes 5 percent of the electrical power. Anything that can reduce these losses would be a valuable investment for electricity suppliers. In May of 2001 some 150,000 residents of Copenhagen, Denmark, began receiving their electricity through HTS (high-temperaturesuperconducting)material.Moreover, funded by the US department of energy, Holbrook Superconductor project involved about 600m of underground cable of BSCCO wire, installed at a Long Island substation in New York. YBCO wires are also being used in a power Station in Clovis, New Mexico. Superconductor-based transformers are also being made as more current can be routed through existing cable tunnels and also making it more space-efficient.

Superconductors also have other uses, especially for specialized applications where cost is less significant. Among these are superconducting magnets. Wire made from a superconducting material is wound to form a solenoid. High currents made to flow around the solenoid produce strong magnetic fields with flux densities up to 20 teslas, roughly half a million times the strength of the earth's magnetic field. The high current required for such enormous fields would cause conventional electromagnets to overheat.

Superconducting magnets are used in magnetic resonance imaging body scanners, which can show up details of the inside of a patient's body without the need for surgery or harmful radiation such as X-rays or gamma rays. Superconducting solenoids are also used to levitate some of the world's fastest trains. "Maglev" trains are supported by the repulsion between the opposite poles of on-board solenoids (which must be cooled) and non-superconducting solenoids in the track reaching a speed of 581kph in Yamanashi superconducting prototype, Japan as levitating the trains cuts out the friction between the trains and the track. Complex, high-speed electronic circuitry is needed to adjust the currents flowing and keep the train at a constant height above the rails.

Particle accelerators around the world also use superconducting magnets. For example, at Fermilab near Chicago, superconducting magnets keep protons orbiting a circular tunnel more than 2 kilometers in diameter. The more energetic the particles being studied, the faster they move and stronger the field needed to keep them in the curved path. Only superconducting magnets are strong enough. In total, over 1,600 superconducting magnets are installed, weighing over 27 tonnes in large Hadron Collider (LHC), the world's largest and highest-energy particle accelerator. Approximately 96 tonnes of liquid Helium is needed to keep the magnets, at their operating temperature, making the LHC the largest cryogenic facility in the world at liquid helium temperature.

On a smaller-scale superconductors are used in electronic devices. In a Josephson junction, the insulating layer is only a few atoms thick, and small currents can flow through it. But if the current exceeds a critical value, the junction switches to a high resistance state and the current is switched off. In this way a Josephson junction can act as an electronic switch. It can switch very fast-within a picosecond (10-12 second). Such switches could be used instead of transistors to build supercomputers that can run perhaps twenty times as fast as today's fastest machines.

The Josephson junction is also used in another electronic application, the sSQUID. One or more junctions are formed into a loop, and when a magnetic field passes through the loop it includes a current. Tiny changes in the magnetic field produce measurable changes in the current, so a SQUID can be used as an extremely sensitive device for measuring magnetic fields. SQUIDs can detect changes that are less than a billionth of the strength of the Earth's magnetic field, and this has given rise to many practical applications. For instance, geologists use SQUIDs in search for minerals.

Chemists use them for monitoring corrosion. And biophysicists use them for imaging activity in the human brain and heart, by detecting the magnetic fields arising from electric currents flowing in the body known as the magnetocardiography or magnetocepholography.

Superconductivity undoubtedly ranks among the ultimate in beauty, elegance and perfection, both theoretically and experimentally of all the discoveries in condensed-matter-physics during the last 100 years. World over we have seen the commemoration of the 100th birthday of these wonderful materials [14] providing new insights and incentives to the physicists in this area. However, the dream of a levitating car, a world without resistance is still a distant future. Yet, we expect a lot more advances both in the theoretical and experimental sector of superconductivity to one day reach the so cherished room-temperature superconductivity. Researchers from all over the world are busy to see the future better in an area which fetched the most number of Nobel prizes and promises a cold technology to revolutionize our future.

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Nobel Prize for Superconductivity

1913 **Heike Kamerlingh Onnes** on Matter at low temperature

1972 **John Bardeen, Leon N. Cooper, J. Robert Schrieffer** on Theory of superconductivity

1973 **Leo Esaki, Ivar Giaever, Brian D. Josephson** on Tunneling in superconductors

1987 **Georg Bednorz, Alex K. Müller** on High-temperature superconductivity

2003 **Alexei A. Abrikosov, Vitaly L. Ginzburg, Anthony J. Leggett** on Pioneering contributions to the theory of superconductors and superfluids.