Low Temperature Physics[1]

Commission 5

Tomasz Dietl, Hidetoshi Fukuyama, Mikko Paalanen, and Dieter Vollhardt

Ever Lower

The hallmarks of low temperature physics have been the quest for ever-lower temperatures, the remarkable discoveries along the way and the many studies of the workings of quantum mechanics at the macroscopic scale. Very roughly, over the past century or more the record low temperature has been reduced by a factor 10 every 10 years. The background temperature of the universe, 3 degrees above absolute zero (3 K), was overtaken in 1908, and 10^{-10} K was achieved in 2000 in a cascade nuclear cooling experiment with rhodium metal. To put this in perspective, particle physicists have achieved similar progress from keV electrons at the turn of the century to TeV protons and electrons at Fermilab and CERN, and over a shorter interval the semiconductor industry has miniaturised from the first mm-sized transistor to single electron and molecular devices, again about a factor 10 every 10 years. No other human achievement comes close!

The landmarks in this quest have been: the liquefaction of helium at 4 K in 1908 by Heike Kamerlingh-Onnes*[2]; magnetic cooling of solids proposed in 1926, independently, by Peter Debye* and William Giauque*; refrigeration to 0.002 K from the dilution of liquid ^{3}He with liquid ^{4}He, suggested by Heinz London, shown to work by P. Das in 1964, and perfected by many others over the following decade; magnetic cooling of nuclei proposed by C. J. Gorter in 1934, realised by Nicholas Kurti in 1956 and most famously by Olli Lounasmaa in 1970; and finally laser cooling of atoms,

---

[1] Updated from the previous article by Marcel Ausloos, George V. Lecomte, John Harrison, and Matti Krusius

[2] Many Nobel prizes have been won in the field of low temperature physics. Nobel prizewinners cited here are indicated by an asterisk * after their names.

first proposed by T. Hansch and A. Schawlow in 1975, shown to cool into the μK region by Steven Chu*, even lower by William Philips* when combined with a magnetic trap, and sub-μK with refinements proposed by Claude Cohen-Tannoudji* in 1989. The laser cooling of atoms has thus been demonstrated to produce 2-3 nK temperatures.

Discoveries

Superconductivty

Low temperature physicists are proud of the string of fundamental discoveries in the field of condensed matter physics. Some were serendipitous and some resulted from dogged searches in response to a theoretical challenge. The first and still perhaps the greatest was superconductivity in a metal: at a low enough temperature well over half the metals in the periodic table, as well as many alloys and compounds, enter a state where their resistance to current flow disappears. If the superconductor is a wire loop and a current is generated in that loop, then it flows for years with no significant decay. The current flow is not deterred by impurities, atomic vibration or crystalline defects. Discovered by Kamerlingh-Onnes in 1911, a satisfactory understanding was not achieved until 1957, in the theory of John Bardeen*, Leon Cooper* and Robert Schrieffer*. They showed that the electrons form into pairs and that the motion of these pairs becomes very highly correlated. Together, the electrons can be described by one wave function or order parameter.

Rather than closing the story of superconductivity, the theory was innovative enough to be adopted in many other areas of physics. Implicit in the theory was the existence of an upper limit to the superconducting transition temperature of about 25-30 K, but to some people any such limit forms a challenge. New classes of superconductor were found but the upper limit still seemed to be 23 K. This was the background for the enormous excitement that accompanied the discovery of a high-temperature superconductor by Georg Bednorz* and Klaus Alex Mueller* in 1986 and the rapid discovery of many others soon after. The upper limit has been pushed up to 160 K in these exotic copper-oxide compounds, and many theorists are still trying to come to a full understanding of the underlying mechanism. At the same time the search for new superconducting materials is still going on and has led to many unexpected discoveries in recent years. For example, in strontium ruthenate (Sr_2RuO_4), whose structure resembles that of the high temperature cuprates, a type of superconductivity was discovered which is similar to superfluidity in Helium 3. Novel materials such as buckyball (C60) compounds and even ferromagnets were found to become superconducting. And most recently the simple intermetallic compound MgB_2 turned out to become superconducting at an astonishingly high 40 K. Clearly, the quest for superconductivity will continue to lead to many more surprises in the future.

The Josephson effect

In 1962, Brian Josephson*, a Cambridge graduate student, presented two equations describing how the electron pairs responsible for superconductivity can "tunnel" from one superconductor to another across a very narrow gap. The "tunnelling" current is driven not by a voltage, but instead by the difference in the coherence factors, $f_1 - f_2$, of the electron pairs in the two superconductors. Again, this is quantum mechanics operating at the macroscopic scale. If a voltage difference V is applied then the tunnelling current oscillates at a frequency given by $(2e/h)V$ where e is the electron charge and h is Planck's quantum of action. Both equations were soon verified and yet another major field of research was created. Josephson's equations showed that $f_1 - f_2$ is very sensitive to small magnetic fields and that so therefore is the tunnelling current. This paved the way for the invention of very sensitive magnetometers. There is no significant radiation from the oscillating current generated by a voltage because of the impedance mismatch between a tunnel junction and free space. However microwave radiation can be mixed in with the tunnel current and so-called Shapiro voltage steps measured, which correspond to $f = (2e/h)V$. One major application has been the present voltage standard defined by this equation and realised with a Josephson junction. Josephson junction circuits have been a test-bed for quantum mechanics and have led to a quantum theory of circuits which will have important implications for the future of electronics.

Superfluidity

The discovery that should have come first but which eluded experimentalists for 30 years was the superfluidity of liquid ^{4}He below 2 K (Piotr Kapitza* and Jack Allen in 1938). The superfluid shows persistent mass flow or zero viscosity and supports quantised vortices. A complete theory of superfluidity has been a much greater challenge, but through the work of Lev Landau* and Richard Feynman* in particular we have a very good phenomenological understanding. Once again, we view all of the helium atoms as moving coherently and described by a macroscopic quantum wave function.

For 50 years liquid ^{3}He, the light isotope of helium, has been acknowledged as an analogue of the electron gas in a metal; the ^{3}He atom and electrons both act as gases of spin-1/2 particles. There was excitement after the understanding of superconductivity that ^{3}He atoms might form pairs and condense into a macroscopic quantum state. After several frustrating searches, the quest was abandoned. However, while looking for something else, the transition was discovered by Doug Osheroff*, Dave Lee* and Bob Richardson* in 1972, at 0.003 K. This discovery opened a new field and rejuvenated very low temperature physics in a way that was seen later in high temperature superconductivity following its discovery by Bednorz and Mueller. The ^{3}He transition was again into a superfluid state but this new superfluid was far more complex with exotic texture and magnetic properties. A very remarkable aspect of the developments after 1972 was the way in which experiment and theory moved along together. Indeed, theory was able to point the way to new phenomena with great precision. The uniquely rich symmetry structure of superfluid ^{3}He later led to the discovery of deep connections with particle physics leading to prediction of the Higgs boson. The theory of superfluid ^{3}He even made it possible to quantitatively test, and confirm, a theory of defect formation in the early universe.

Bose-Einstein condensation

In this short history, the final remarkable discovery resulted from a systematic programme of research highlighted by brilliant experimental techniques. The goal arose from one of Einstein's predictions from 75 years ago. In 1924 Satyendra Bose sent to Albert Einstein* a paper in which he had created quantum statistical mechanics. Einstein appreciated this, arranged to have it published, and then developed the ideas. He found in the equations that if a gas of integer spin particles (e.g. the hydrogen atom) was cooled sufficiently all the atoms should condense into the same quantum state. While ^{4}He atoms in superfluid helium and the electron pairs in a superconductor bear a resemblance to this Bose-Einstein condensation, the strong interactions prevent them from mimicking Einstein's model system. For many years several groups searched for this holy grail with hydrogen gas and standard low temperature techniques. In fact Dan Kleppner and Tom Greytak did succeed in 1998. Before that though, a group of atomic physicists had taken a different approach. They started with a dilute gas of Rb atoms and slowed the atoms with a set of six lasers. The lasers are tuned to slow atoms that approach them. A set of magnetic field coils were then switched on and trapped the magnetic Rb atoms. Once trapped the outermost atoms are force-evaporated so that the gas becomes colder and smaller in extent. Remarkably, with this elaborate table-top experiment, the final 2000 atoms were cooled to 20 nK, with Bose-Einstein condensation setting in at 170 nK. This achievement by the group led by Carl Weiman* and Eric Cornell* at NIST in Colorado was soon repeated by Wolfgang Ketterle's* group at MIT with 5 million atoms and a transition temperature at 2 μK. Subsequent experiments have confirmed the quantum coherence of the condensate by allowing two condensates to overlap and observing quantum interference fringes. This is a new field with much interesting physics and the potential for the creation and application of atom lasers.

The quantum Hall effect

Klaus von Klitzing* made a remarkable discovery in 1980 when studying the Hall resistance of a two-dimensional semiconductor at low temperature. The Hall resistance is the ratio of the transverse voltage divided by the longitudinal current when a magnetic field is applied. This resistance should be proportional to the magnetic field and inversely proportional to the number of charge carriers. He found, instead, that as he changed the number of carriers the Hall resistance showed a series of very flat steps and that the resistance plateaux were equal to $(h/e^2)/N$, where N is an integer, to better than 10 parts in a million. The precision has since been put at 10 parts in a billion. This is remarkable in a solid with impurities, defects, and atomic vibrations.

The exactness of the Hall quantization has now been explained using a variety of theoretical approaches, but a key insight was provided by Robert Laughlin* in 1981. Using principles of gauge invariance in an annular geometry, Laughlin showed that the Hall conductance would be quantized, in the limit of low temperatures, whenever the electron Fermi level falls in an energy gap or in an energy range where the states are localized by disorder.

There is also a view based on electron transport along one dimensional edge states. In the presence of a crossed electric and magnetic fields, electrons skip along the sample edge without any backscattering, even in the presence of impurities and other defects. According to theory initiated by Rolf Landauer in the 1960s in another context, the corresponding conductance is quantized, provided that the bulk states are localized by disorder and that the voltage difference between the two edges is due to a difference of the chemical potentials, with no electric field inside the sample.

The unit of resistance is now defined in terms of this quantum Hall effect. The precision is such that the resistance of the former standard ohm can be seen to be changing linearly with time, at 50 parts per billion per year. While the quantum Hall effect could be understood in terms of a quantum model, this did not prepare us for what happened next. Horst Stormer* and Dan Tsui* worked with very pure semiconductors, very high magnetic fields and low temperature and found plateaux at *fractional* values of N. The implication was that the elementary charge was not e, but a fraction of e. It was Robert Laughlin who made sense of this, in terms of a composite quasi-particle arising from correlated interactions between the electrons.

Quantum coherence in mesoscopic and nanoscopic systems

The Quantum Hall effect is one of many other manifestations of quantum phenomena in electron transport. David Thouless realised in the 1970s that quantum interference of transmission amplitudes of quasiparticles in solids is destroyed by inelastic scattering processes. Since energy dissipation vanishes at absolute zero, searches for coherent phenomena in electron transport of normal metals have become an important field of low temperature physics. It has been found that interference accounts for localisation of electronic states by disorder, an issue pioneered by Phil Anderson* and Nevill Mott*. Furthermore, quantum interference and quantum repulsion between energy levels in small samples, the latter similar to that discussed by Eugene Wigner* in the context of nuclear states, leads to a universal character of conductance fluctuations and its distribution in an ensemble of nominally identical small conductors, as shown by Boris Altshuler, Patrick Lee, and others. These phenomena make the conductance very sensitive to the actual impurity distribution in a given sample, which among other things explains a large amplitude of resistance changes associated with defect migration in many devices, leading to the existence of $1/f$ noise.

The steady progress in nanostructure fabrication and material quality opened the possibility of addressing experimentally the question whether indeed the resistance vanishes in the absence of scattering centers. In contrast to the classical expectation but similarly to the quantum Hall effect, the wire resistance was found to be quantized, in units of $(h/e^2)/N$, where N corresponds again to the number of one dimensional sub-bands (propagating modes) below the Fermi energy of the channel.

The phenomenon of the Coulomb blockade, occurring when a sub-micrometre capacitor is charged at low temperature, is another example of new effects now in focus in low temperature research, which have led to the concept of the single electron transistor that will be discussed below. In essence, the studies of presently available nanostructures at low temperatures tell us about expected properties of room temperature devices, if progress in miniaturization continues as it has up to now. Investigations of mesoscopic objects, which lie on the border between macroscopic and microscopic worlds, have improved our understanding of the interface between classical and quantum physics. Recently acquired knowledge of mechanisms underlying decoherence, quantum measurement processes, and manipulations with quantum states is deployed in today's quest for quantum information hardware.

Applications

Much of our understanding of metals and semiconductors has come, and continues to come, from low temperature research but on the whole the applications of these materials are at room temperature in the everyday world. The most significant real application from low temperature physics is the superconducting magnet. This seems such a natural application, to run hundreds or thousands of amps through a resistance-less coil of wire and generate a large field with no Joule heating. However, the first superconductors were returned to normal metals by modest magnetic fields. A second type of superconductor that remained superconducting in large fields entered a mixed state at modest fields, with magnetic flux penetration and dissipation as this magnetic flux interacted with the current. Only in the 1960's did materials scientists learn to "pin" this flux and inhibit the dissipation. Then superconducting magnets really took off and are now a billion-dollar industry with most magnets used for magnetic resonance imaging (MRI) and for particle accelerators.

With improvements in high-temperature superconducting materials and in flux pinning methods, further applications of superconductivity can be expected within the next decade. The use of liquid nitrogen as coolant, instead of liquid He, may lead to the commercialization of levitating trains, superconducting motors and generators, as well as superconducting power lines. A possible important niche market for high-temperature superconductors could be the filters used for mobile-phone base stations. The quality and hence resolution of the filters appear to be a factor 10 better than for conventional filters.

Josephson junction magnetometers, called SQUIDs (Superconducting Quantum Interferometric Devices), are incredibly sensitive and have found many applications, particularly in scientific research. They are also used routinely in geophysical exploration and the emerging field of biomagnetism. Their sensitivity allows them to detect magnetic fields from electric currents in the heart and brain. Superconducting electronics, mainly based upon Josephson junctions, has long held great promise. The fundamental switching speed is governed by the Heisenberg uncertainty principle and can exceed terahertz (10^{12} Hz) in high temperature superconductors. This is several factors of ten faster than reasonable limits for semiconducting devices. Their implementation has been held back by the relative lack of investment, the need for refrigeration and the difficulty of achieving large-scale integration with superconducting materials. There is a parallel with alternatives to the gasoline engine: at some point the oil wells will run dry and at some point semiconductors will reach their limit. Recent achievements by Konstantin Likharev and Theodore Van Duzer with rapid single-flux quantum switching devices do look very good. These devices may find application as fast routers between the different parts of parallel computers.

The SQUID is not the only example of a cryogenic supersensor: others are the single electron transistor, low temperature scanning probe microscopes and various bolometers and calorimeters for radiation detection. In general, the noise properties of a sensor improve dramatically at lower temperatures. While not commercial in the usual sense, these low temperature sensors are being used more and more for detectors in fields far removed from traditional low temperature physics; examples include infra-red detectors for astronomy, x-ray detectors for materials science, and calorimeters for neutrino and dark matter searches. Recently, potential applications of single electron transistors are demonstrated in quantum computing and in ultrasensitive bolometers in detection of rare atmospheric gases and of concealed weapons.

The spread of low temperature applications has been slow due to the need for inconvenient cryoliquids. Pulse-tube and on-chip refrigerators, two recent innovations, may change this by providing a cryogen free alternative for low cooling power applications. The pulse-tube cooler, developed during the last 30 years, uses an oscillating gas, usually helium, to pump the heat away from a low temperature platform. It provides a simple, closed cooling system from room temperature down to liquid He temperatures, with no moving parts at the low temperature end. With recent improvements in cooling power and lowest attainable temperatures, use of pulse-tube coolers is increasing fast in applications where mechanical vibrations are not critical. In the tiny on-chip refrigerators the cooling is produced by evaporating hot electrons over a tunnel barrier. Thanks to the decoupling of electrons and phonons below 0.3 K, the temperature of the remaining electrons can be decreased well below the lattice temperature. The application of on-chip coolers looks most promising in increasing the sensitivity of miniaturized sensors and sensor arrays by cooling them from 0.3 K to well below 0.1 K temperatures.

The Future

It would be presumptuous to predict future discoveries, particularly given the complete surprise provided by several past discoveries. The areas where new phenomena and ideas are expected include dilute gas Bose condensates, theories for strongly correlated electrons, unconventional materials, and nanoscale structures and devices, which may have an important impact on nanoscience. In particular, a growing amount of effort will be devoted to the search for promising quantum information carriers as well as to develop concepts of quantum gates suitable for the fabrication of functional processors. One of the ultimate goals of the field referred to as spin electronics or spintronics will be mastering the manipulation of the spin of a single electron in a solid state environment.

Along with presently employed nanolithography methods, self-organization and related means will be developed for nanostructure and nanosystem fabrication, exhibiting complex, often three dimensional architectures. On the materials side, an increasing role will presumably be played by carbon-related materials, starting from carbon nanotubes and related structures, and from molecular solids to more complex organic systems. The rapid advances in micro-machining will lead to refrigeration on a chip and perhaps to widespread applications of superconducting electronics. Superconducting magnetometers will follow MRI out of the research laboratory into clinical use, particularly for imaging brain function. What can be said is that the excitement generated by past discoveries and achievements is contagious and it is a pleasure to see so many young scientists at the international conferences and gatherings on low temperature physics and technology. These people will leave their mark!