NEWS & VIEWS

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SUPERCONDUCTIVITY

Extraordinarily conventional

Attitudes to high-temperature superconductivity have swung from disbelief to a conviction that it occurs only 'unconventionally'. But conventional superconductivity is now reported at record high temperatures.

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In 1911, the physicist Heike Kamelingh Onnes was puzzled to observe[1] that mercury became an ideal conductor below 4.2 kelvin. How could all the electrons in a metal cooperate so as to carry electric current without resistance? Common wisdom dictates that there is nothing ideal in this world. Nobody's perfect! No crystals without defects can be created, no wheel can roll without friction, no glass can be 100% transparent. Yet subsequent experiments confirmed that the resistivity of many metals suddenly drops to exactly zero at a sufficiently low temperature. Chaotic motion introduced by heat destroys electronic cooperation, so for many years it was believed that this phenomenon, now known as superconductivity, is limited to ultra-low temperatures. But in a paper published on *Nature*'s website, Drozdov and colleagues[2] report a superconductor that works at about 200 K — a temperature that actually exists on Earth's surface.

For decades, physicists were in the dark about the origin of superconductivity. The discovery in 1938 of another cooperative phenomenon[3] — superfluidity in helium at 2 K — offered the first clue[4]. This complete lack of viscosity turned out to be a direct consequence of quantum mechanics. All quantum particles are characterized by a 'spin' number; if this is an integer (as for helium-4 atoms), the particles can combine into a single object so large that it cannot be disturbed by such nuisances as friction or viscosity. This effect is called Bose–Einstein condensation.

But electrons, which conduct electricity, have a spin of ±½, and so are not subject to Bose–Einstein condensation. In 1957, John Bardeen, Leon Cooper and Bob Schrieffer therefore proposed that the interaction of electrons with metal ions creates an attractive interaction that forces the electrons to combine in pairs[5]. These 'Cooper pairs' have a net spin of zero, and can form a Bose–Einstein condensate. This theory also allows the transition temperature, T_c, below which superconductivity occurs for a given metal, to be estimated.

Most elemental superconductors had been discovered by 1957, and all had T_c values of less than 10 K. For the next two decades, scientists worked with various compounds, but failed to increase T_c by even a factor of three. Not surprisingly, most physicists began to believe that nature imposes a fundamental, but as-yet unexplained, T_c limit of 25–30 K. The problem was succinctly formulated by the materials scientist Bernd Matthias in 1964: "Why has it been relatively easy, within the last 10 years, to reach transition temperatures of 17 to 18 K in many intermetallic systems and impossible to raise this value even by as little as half a degree?"[6] Eight years later, Marvin Cohen and Phillip Anderson pointed out that if electrons interact too strongly with the ions in a metal, they can break the lattice apart[7]. On this basis, they estimated that the highest T_c for conventional superconductors (those driven by the electron–ion interaction) is approximately 30 K.

> ***"A previously unknown material predicted to be a high-temperature superconductor has been experimentally confirmed to be one."***

Although the argument seemed convincing, some physicists remained hesitant. In the early 1970s, Vitaly Ginzburg — one of the top theorists of the time — organized a group in Moscow to explore routes to high-temperature superconductivity. One of his team's principal results was that a key assumption by Cohen and Anderson was flawed, and that T_c could, in principle, be arbitrarily high even in a conventional superconductor[8].

Another prominent physicist who did not subscribe to the idea of a universal limit was Neil Ashcroft. In the late 1960s, he[9] and Ginzburg[10] proposed that, if hydrogen could become metallic, the energy of its ionic vibrations would be so high that even a moderately strong electron–ion coupling could result in a rather high T_c. Unfortunately, metallization of hydrogen has proved to be extremely difficult. It was then pointed out that hydrogen-rich compounds might be better targets[11,12], but it is only now that this idea has been realized, as reported by Drozdov and colleagues.

In the meantime, three major breakthroughs occurred in superconductivity. First, cuprate superconductors were discovered[13] in 1986; within seven years, the T_c for these compounds reached 133 K (ref. 14). These have been recognized as 'unconventional' superconductors, driven by interactions among electrons, rather than by electron–ion interactions.

The second was the discovery[15], in 2001, of magnesium diboride — a conventional superconductor whose T_c is 40 K. This relatively high number is due to the low mass of boron, and to the fact that strong electron–ion coupling is ensured because the conducting electrons come from the boron, and the boron ions form a rigid sublattice. The physics of superconductivity in magnesium diboride turned out to be considerably more complex than for other conventional superconductors known at the time, but was understood within a year of the original discovery. At last, theorists could accurately calculate the critical temperature of a rather complicated material. This encouraged scientists to seek quantitative predictions for new superconducting materials.

The third breakthrough was the discovery[16] of iron-based superconductors in 2008. These materials seem to be unconventional and, although of great interest, have never surpassed the T_c of the cuprates.

Drozdov and co-workers report a fourth breakthrough: superconductivity at approximately 200 K in a hydrogen-rich compound, sulfur hydride, at about 90 gigapascals — a pressure hardly achievable just a few years ago. Not only is this a 50% increase over the previous record for T_c, but the authors convincingly argue that the observed superconductivity is conventional, vindicating the ideas of Ashcroft and Ginzburg.

Moreover, this is the first time that a previously unknown material predicted to be a high-temperature superconductor has been experimentally confirmed to be one. A computational study[17] of hydrogen-rich materials under pressure had reported that the sulfur hydride H_3S would be a superconductor with T_c in the range 190–200 K at 200 gigapascals — very close to the now-reported experimental value. Drozdov *et al.* studied H_2S, but it seems that at high pressure this decomposes into elemental sulfur and hydrogen-rich H_3S. It is therefore highly likely that the superconducting material is H_3S. More-accurate calculations[18–20] yielded a T_c value approximately 20% higher than in the earlier computational study[17]. There is some disagreement about which small effects, not accounted for in standard computations, are responsible for this overestimate, but it is amazing that theorists quibble about a 20% inaccuracy in first-principles calculations when even an order-of-magnitude estimation was considered practically impossible only 40 years ago.

In 1796, the philosopher Wilhelm Hegel introduced the concept of spiral progress: an intellectual proposition is superseded by its negation, but later the negation itself is negated; the original thesis is then reinstated, but at a higher level of development. The generality of this concept can be philosophically disputed, but Hegel's idea seems to be confirmed by the fact that the holy grail of superconductors has been discovered in the same group of materials as the first known superconductors, after a tiresome quest along exotic routes. ■

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