SUPERCONDUCTIVITY: ADVANCES AND PROSPECTS

Discovered 100 years ago by Heike Kamerlingh Onnes and his team on the 8th of April 1911, the phenomenon of superconductivity continues to fascinate. The familiar demonstration of levitation that all of you have seen amazes scientists and the public alike. Perhaps the most surprising aspect to the physicist is the wide variety of contexts in which superconductivity manifests itself: in solids of course, but also in cold atoms, superfluid helium-3, nuclear matter, and neutron stars. Within the standard model of elementary particles, the vacuum is an electro-weak superconductor. Superconductivity is widespread in physics.

The transport of electricity without resistance immediately suggests applications. Power transmission of course, but also resonators for wireless communications and electromagnets for medical imaging and levitating trains. Superconductors bring the magic of quantum mechanics to the human scale: not only levitation, but also coherence. The superconductor is to electricity what the laser is to light: it is the coherent form of electricity. Coherence in superconducting rings is used not only to make the most sensitive detectors of magnetic fields but also qubits, those quantum bits that may some day be the basis for a quantum computer.

As for many other phenomena, superconductivity had to wait for the advent of quantum mechanics to be understood. The solution proved remarkably difficult to find, even for such geniuses as Einstein, Heisenberg and Feynman. There was no direct path leading from the Schrödinger equation to superconductivity. Two new concepts were needed: the Cooper pair and broken symmetry. The latter was not entirely new, but it really came into its own with the theory of Bardeen, Cooper et Schrieffer (BCS) in 1957. Those two ‘emergent’ concepts are still the basis for our understanding of the superconducting state.

BCS also proposed a mechanism by which electrons would spontaneously form Cooper pairs: an attractive interaction mediated by the vibrations of the surrounding lattice of ions. Proven to work in conventional superconductors, this phononic mechanism failed to describe the properties of copper-oxide (cuprate) superconductors discovered 25 years ago, whose critical temperature is exceptionally high (up to 164 K). Other mechanisms are now being considered and there seems to be no fundamental law of physics that forbids superconductivity up to room temperature. Because of the green revolution it would cause in the realm of power transmission, Scientific American declared in its June 2010 issue room-temperature superconductivity to be one of ‘twelve events that will change everything’.

The pairing mechanism is the Holy Grail in the field. New materials are constantly being discovered, with superconductivity showing up in the most unexpected places, from organic conductors to iron pnictides. Guided by the original phononic mechanism, one would be taken away from magnetism, insulators and oxygen. Instead, scientists are now looking for characteristics of this kind in their quest for unconventional superconductors that can survive up to high temperature. The study of materials in which electron behaviour is dominated by strong correlations is a promising frontier of research, not only because of the potential for superconductivity but also because of the many ways in which it goes beyond the physics of solids as we currently know it. Fresh insight into Mott physics, magnetism and quantum criticality, for example, is required for a vast class of materials.

This issue of Physics in Canada provides a survey of superconductivity research and it highlights the Canadian contribution to this thriving international field. The impact of this contribution is out of proportion with the size of the Canadian scientific community, in good part because of the spirit of collaboration fostered by the Canadian Institute for Advanced Research whose program on Quantum Materials has for the past 20 years brought together materials scientists, experimentalists and theorists throughout Canada and the world. The success of Canadian research also comes from the freedom given to researchers by granting agencies such as NSERC and CFI. Future advances on the road to room temperature superconductivity will depend crucially on freedom and collaboration, world-wide. May the second century of superconductivity research be characterized by such spirit.

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Comments of readers on this editorial are more than welcome.