Conference summary

The International Conference on Low Temperature Physics is an international meeting held every three years, under the auspices of the International Union of Pure and Applied Physics (IUPAP) through its Commission C5 on Low Temperature Physics. The aim of these conferences is to exchange information and views among the members of the international scientific community in the general field of low temperature physics. It is a tradition that the breadth of scientific research that takes place at low temperatures and makes use of, or contributes to, low temperature physics technologies, finds a commonality in this international conference series. The LT28 conference was organized in this tradition to provide updates on various topics by distinguished researchers in their fields, including plenary and half-plenary talks, invited and contributed oral presentations, and posters. The conference covered five subtopics which have evolved since the last few conferences in this series. These are Quantum fluids and solids, Superconductivity, Cryogenic techniques and applications, Magnetism and quantum phase transitions, and Quantum transport and quantum information.

Gothenburg is situated in the center of Scandinavia, on the Swedish west coast, and is easily accessed by air. The city’s two universities, Chalmers University of Technology and the University of Gothenburg, were the official conference hosts. Both have a long tradition in low temperature physics research, particularly superconductivity, quantum transport, and quantum information.

In this report we summarize some of the scientific achievements that were presented at LT28. Although this is not a comprehensive account of the meeting, it should be considered as representative of its program which is detailed in the schedule and abstracts available on-line.

Quantum fluids and solids. The significance of topology and topological defects in phase transitions in two-dimensional systems was recognized through the award of the 2016 Nobel Prize to Michael Kosterlitz, David Thouless, and Duncan Haldane. Its experimental manifestation in thin films of superfluid $^4\text{He}$ was precisely described by the theory of the Kosterlitz-Thouless transition which has also found application in a wide range of quantum condensed states including superconductivity, two dimensional melting and two dimensional magnetism. Topological structure and topological defects was a recurring theme of emphasis in this conference including superfluid $^3\text{He}$ and unconventional superconductors. A physical object within a superfluid medium, in relative motion with respect to the fluid, is expected to exhibit a threshold for onset of dissipation called the Landau critical velocity. Novel results with rather different interpretations in the case of superfluid $^3\text{He}$-B, both theory and experiment, were compared and discussed. The properties of the superfluid near the surface of the object play a crucial role in this case, specifically the surface-Andreev bound states of the superfluid that can be identified with Majorana fermionic excitations. Such exotic quasiparticles are of great current interest, and are of potential importance in topological quantum information processing. They were discussed in a wide variety of quantum materials: superfluid $^3\text{He}$-B (measurements of ion mobility, heat and mass transport, specific heat); ad-atom chains; Cooper pair transmission at an interface between a normal metal and a nodal superconductor; spin liquids; topological insulators; magnetic atom chains on elemental superconductors; half-quantum vortices in the recently discovered polar state of superfluid $^3\text{He}$-B.

Superfluid $^3\text{He}$ was discovered in 1972 and was first reported at the LT13 conference held later that year. Its importance is underscored by Nobel prizes in 1996 and 2003. This superfluid is a paradigm for a wide range of physics of unconventionally paired fermionic systems. Recent work on topological superfluid $^3\text{He}$ was reported at LT28 in quasi two-dimensions for slabs; quasi one-dimension for pores, and in three dimensions for superfluid $^3\text{He}$ imbibed in various kinds of aerogel. In the latter case the effect of
quenched disorder on superfluid phase stability and symmetry is remarkable including the first observation of the polar phase of superfluid $^3$He and, in this phase, the existence of half-quantum vortices. The discovery and understanding of superfluid $^3$He in aerogel was recognized at LT28 by the award to William Halperin, Jeevak Parpia, and James Sauls of the Fritz London Memorial prize sponsored by the C5 commission of IUPAP and Oxford Instruments and administered by Duke University, “For pioneering work on the influence of disorder on the superfluidity of Helium-3”. Two dimensional films on atomically precise surfaces of graphite show intertwined superfluid and density order for $^4$He. In contrast, there is evidence that a $^3$He film on graphite at ultra-low temperatures is a spin liquid at certain coverages. Superfluid $^4$He counterflow in square channels evolves from Poiseuille flow and is related to the problem of onset of turbulence that has been investigated using linear displacement of a grid. In bulk $^4$He, phonon and vortex ring emission have been modeled; however, from recent work vortex reconnections are found to be primarily identified with roton emission. The full development of the excitation spectrum of $^3$He has been determined from inelastic neutron scattering, now well-understood theoretically and consistent with experiment. The community of researchers focused on cold atomic gases has strong intellectual links with that working on liquid helium, while using very different experimental techniques. Progress was reported on using cold atoms in optical lattices to engineer many-body systems as analogue quantum simulators. Studies of mesoscopic transport, including the observation of quantized conductance for neutral particles and quantum interference in transport, vortex dynamics and turbulence, and the observation of rotons in cold atom systems with both short and long-range (dipolar) interactions, illustrate the strong link to condensed matter physics.

Superconductivity. An important goal is topological superconductivity, where topological insulators (TI) are a promising host as indicated in the superconductor Cu$_x$Bi$_2$Se$_3$ which has been shown to have nematic order. The behavior of TI-based materials is one of the most active areas today in condensed matter physics, largely motivated by the expectation that the topological character of superconductivity that can be stabilized will be a major step toward quantum information processing. Recent work in this area was recognized with the award at LT28 to Vlad Priimag of the Young Investigator Prize from the C5 commission of IUPAP on “Electronic Transport in Semiconductor Nanowires and 2D Topological Insulators”. Improvement in cuprate superconducting materials, both electron and hole doped, are giving better resolution and understanding of transition temperatures such as the role of the apical oxygen site probed by ARPES and also by NMR. New theoretical work indicates the existence of vortex-antivortex pairs at the edge of a $d$-wave superconductor which should be verifiable experimentally. Anti-perovskite oxides like Sr$_{3-x}$SnO open the possibility of topological odd-parity superconductivity. The superconducting ruthenates Sr$_2$RuO$_4$ and Ca$_2$RuO$_4$ have special properties. For the former, a transition from odd-parity to even parity under strain has been reported. The measurements of strain dependence were acknowledged at LT28 by the award to Clifford Hicks of the Young Investigator Prize from the C5 commission of IUPAP, “Correlated Electron Materials Under Uniaxial Stress”. In the latter case of the calcium compound, closing of the Mott gap leads to emergence of a semimetal state with giant diamagnetic behavior. A classic example of quantum criticality is manifest in hole-doped cuprates. Heavy fermion compounds provided the first paradigms of quantum critical behavior, where in many cases unconventional superconductivity appears at the quantum critical point. Examples that have been discussed at LT28 include CeIrSi$_3$, CeCu$_2$Si$_2$, CeCoIn$_5$ and uranium based compounds, URu$_2$Si$_2$ URhGe, and UPt$_3$. The use of tuning parameters such as magnetic field or pressure is important for demonstrating quantum criticality. Ferromagnetic uranium-based superconductors such as UGe$_2$, URhGe, or UCoGe, are thought to be odd-parity; ferromagnetic fluctuations are evident in NMR and inelastic neutron scattering. Coexistence of superconductivity and magnetic order is well documented in these materials. Similarly, coexistent spin density wave order is evident in both hole and electron doped pnictide superconducting compounds. These results from reports at LT28 are consistent with what is now the very well-accepted understanding in many different classes of compounds that suppression of magnetic order,
at a quantum critical point, by doping or pressure is concomitant with the emergence of superconductivity.

**Cryogenic techniques and applications.** The development of commercially available cryogen-free cryogenics, notably dilution refrigerators, has had an important impact on low temperature physics research, especially in the past three years. This technology has expanded to include cryogenic platforms for nuclear demagnetization cooling to ultra-low temperatures, superconducting magnets, and development of various protocols for reduction of vibrations from the dry coolers that replace liquid helium as a temperature reservoir. Applications of dry refrigerators provide a means to mitigate the increasing cost and limited availability of liquid helium, which will become more severe with the closing of the helium reserve in the United States in 2021 that supplies a major fraction of the world supply of helium (30% in 2013) used by the international low temperature research community. For example, dry refrigerators operating near 0.02 K have been used extensively in the rapidly developing field of research on quantum information processing that has the overarching goal of quantum computation and the development of quantum computers. Basic research in cryogenic techniques has the dual impact of supporting programs in fundamental physics as well as for its applications, both of which were significantly represented at LT28. The development of micro-calorimetric methods using modern clean room fabrication techniques to create two dimensional arrays with high resolution readout have potential metrological application in nuclear physics and particle physics. Also for these purposes, microwave detectors with unprecedented energy resolution have been demonstrated using sub-gap superconducting resonators. High sensitivity SQUIDs for various types of magnetic measurements have been developed for measurements of systems in the extreme environments of ultra-low temperatures and high magnetic fields in excess of 10 Tesla. Among many types of measurement based on the SQUID, are NMR, magnetization, torque, and thermometry methods having many orders of magnitude greater sensitivity than in the earliest work (a SQUID application at ultra-low temperatures was first announced at LT12, 48 years ago). Cryogenic detectors now take advantage of nanofabrication techniques, including on-chip demagnetization coolers and ultra-low noise amplifiers discussed at LT28. Opto-mechanical devices operating near the mechanical quantum ground state have important technological application for frequency transduction, an essential component for quantum communication. These fabrication tools have led to development of high sensitivity mechanical devices at very low temperatures, with strong interest in nano-electromechanical devices and nano-superfluidics, for example.

**Magnetism and quantum phase transitions.** Research on quantum materials with exotic ground states requires, in many cases, low temperatures for their investigation. Frustrated magnetism in correlated oxides with strong spin-orbit interactions is an example. New compounds and those with higher quality crystal structure or purity have revealed dimensional effects that have been determined using neutron scattering. Iron dichalcogenide ladder compounds with competing magnetic and superconducting interactions have been synthesized, with BaFe$_2$Se$_3$ being the first in its family found to be superconducting. Their magnetic dynamics have been reported from neutron and muon scattering experiments at low temperatures. Intriguing recent results on the Kondo insulator SmB$_6$, which appears to show a bulk Fermi surface, were reported. The spin liquid is a highly quantum entangled state of matter in search of a material which unambiguously realizes it: the current status of this search was reviewed. For example, magnetic frustration induced by dimensional or geometrical constraints, as with the topological honeycomb materials, are candidates for spin-liquid behavior. Similarly spin-stripe materials have been of great interest in both experimental and theoretical research, an example being the elementary excitations in the vanadate compound TeVO$_4$ that were investigated by muon relaxation and dielectric loss spectroscopy. The counterpoint between spin-ice and spin-liquid ground states has been of great interest at LT28. The magnetism in the high field Q-phase of the heavy fermion compound CeCoIn$_5$ and a possible connection to orbital order was reported from scanning tunneling experiments with potential significance for the mixed spin and orbital orders observed in the superconducting cuprates. Inelastic
neutron scattering is a measure of magnetic fluctuations. A good example from the family of uranium based heavy fermion ferromagnetic superconductors is URhGe where small angle neutron measurements give a complementary, and possibly inconsistent, picture as compared with recent NMR results on the same material. Improvements in crystal quality will be very helpful for better understanding the interplay between magnetism and superconductivity in this special class of quantum materials.

**Quantum transport and quantum information in condensed matter.** Quantum transport and mesoscopic physics include important and traditional topics presented and discussed at most LT conferences and LT28 was no exception. What is new is the significant growth in research presented concerning quantum information in condensed matter systems. The latter ranges from the invention and investigation of new qubit systems including spin-qubits from semiconducting nanodots and superconducting qubits based on coupling Josephson junction to microwaves in superconducting resonators. Multi-terminal Josephson junctions are predicted to have topological properties with different phases of what can be considered as a form of quantum matter. Majorana fermionic excitations have been actively sought in condensed matter materials associated with nanowires. They are also expected at the surface of an unconventional superconductor, such as the B-phase of superfluid $^3$He, otherwise known as surface-Andreev bound states. These particle-like excitations, or anyons, have non-abelian statistics and are expected for the $\nu = 5/2$ state in the fractional quantum Hall effect. Although this statistical behavior has not yet been demonstrated, a possible manifestation of the latter by an entropic test has been reported at LT28 in the context of thermodynamic measurements on a high mobility heterostructure. Superconducting qubits based on microwave cavities coupled to Josephson junctions have been improved, increasing the coherence time through significant improvements in device and materials physics and engineering. It has also been shown that super-adiabatic protocols can be a very robust route to efficient quantum state manipulation of quantum information. For a flux qubit, the role of universal conductance fluctuations limiting the coherence time have been studied theoretically. Circuit-QED experiments were presented demonstrating photon entanglement achieved using a two-mode resonant circuit. It was also found that quantum dots in a hybrid light-matter state coupled to cavity photons can be sufficiently well-coupled that they protect entanglement over ultra-long distances. Mesoscopic devices that control heat transfer using superconducting qubits have been developed that promise the experimental realization of a quantum refrigerator. Quantum transport theory suggests that quantum criticality and super ballistic transport can be achieved in a tunable circuit. Electrical transport in a graphene bilayer with superconducting NbSe$_2$ contacts have been shown to exhibit specular Andreev reflection. There is broad interest in quantum matter consisting of semiconducting two-dimensional Bi$_2$O$_2$Se. Notable for understanding the electronic behavior in nano-plates of this material are the reported observations of quantum oscillations, paving the way for future device fabrication. Recent work on quantum oscillations in cuprate superconductors, using high magnetic fields to suppress superconductivity was presented, with evidence for a quantum critical point. This and prior work was celebrated at LT28 by the award to Louis Taillefer of the Simon Memorial Prize in Low Temperature Physics administered by the Institute of Physics, “For pioneering transport measurements at high magnetic fields and low temperature in heavy-fermion and cuprate superconductors.”

LT28 conference summary respectfully submitted by,

William Halperin, Secretary
John Saunders, Chair
*IUPAP Commission C5*