Low-Temperature Physics Today

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Low temperatures have long been common in condensed-matter physics, and more recently in atomic physics (they have always been so in theory, of course, with the basic concepts of the ground state and elementary excitations). Some laboratories — the CRTBT among others — are squarely dubbed centres for low-temperature research. A cooperation of two fields a laboratory such as ours can tackle, shall adopt a more generic point of view. The various essential "functions", and the relevant interfaces with other fields, of a centre for low-temperature research will by presented vertically, so to speak, without attempting to be exhaustive.

The founding masterpiece of low-temperature physics dates back to 1908 with the liquefaction, at Leiden, of 4He. This made available temperatures 70 of 4 K and opened the way, three years later and again in Kamerlingh Onnes's group, to the discovery of superconductivity. By pumping on the liquid, the minimum temperature reached is 1.1 K for 4He and 0.3 K for 3He. Lower temperatures were eventually obtained by adiabatic demagnetization, but steady-state operation has, to wait for the 4He-3He dilution refrigerators which progressed down to the mK range in the early 1970's. These cryostats are based on the Fermi liquid properties of 3He at very low temperatures. In fact, in contrast to the 4He isotope, 3He has a nuclear spin of 1/2 and obeys Fermi statistics. Its enthalpy H therefore depends strongly on the density x such that $H = -T_F^{-1} - x^{2/3}$ where $T_F$ is the Fermi temperature. At a given temperature, the dilution of 3He in a solution rich in 4He decreases the density and increases the enthalpy of the system. As the solubility of 3He is limited to 6.2% at low temperature, it is possible to work along the phase separation line which results in strong cooling by adiabatic dilution ($T_\text{final} = 0.3 T_\text{initial}$). The use of heat exchangers to pre-cool the mixture allows the cryostat to operate between 2 mK and 1 K with a cooling power ranging from 0.1 mW to a few mW, depending upon temperature and circulation of dilution gas.

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Bolometry
Recent developments in bolometric selection have yielded spectacular improvements in energy resolution for various types of radiation; cooling to 10-100 mK using a dilution cryostat is generally required. For measurements of particles or electromagnetic radiation, the most commonly used detector exploits a semiconductor to convert energy into electron-hole pairs. This allows direct measurements but presents two main disadvantages: the energy gap prevents the detection of low-energy particles and the energy dissipated in the detector originates from both the detection process (pair generation) and heating of the detector.

Bolometers are able to measure this energy require a 10 kg crystal of Ge cooled to 10 mK.

Quantum Fluids
Polarized 3He
The microscopic description of 3He remains controversial. It is probably the simplest example of a Fermi liquid, i.e., a liquid made of interacting, degenerate fermions (other examples are electrons in metals and neutrinos in nuclear matter). Understanding

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Laboratories specialising in low temperatures offer natural meeting points for research and technical development, where progress today lies at the crossroads between frustration and disorder and their quantum-level coherence and dynamics.
can be improved by studying the effect of polarizing the nuclear 1/2 spins to make $^3$He atoms more alike, and to increase the influence of the Pauli principle, thereby modifying thermodynamic and transport properties. Several experiments have been performed during the last decade to determine these modifications, but a fundamental difficulty is to obtain significant nuclear polarization. Owing to the weakness of the $^3$He nuclear moment combined with Fermi statistics, a magnetic field of 30 T (today's limit for static fields in the laboratory) polarizes the spins by only 10% (55% up spins, 45% down spins). However, larger polarizations are possible out of equilibrium due to the long magnetic relaxation time (several hundreds of seconds).

We are presently using two different methods based on this idea. In the first, an initial large polarization is obtained by melting a highly spin-polarized solid (typical polarization of 80% at 5 mK in a 1 T field). It has recently allowed the magnetization curve of spin-polarized $^3$He to be measured up to 200 T [5]. An original aspect of the experiment is that the effective field for the $^3$He atoms is deduced from the heat released during the relaxation process. The results (Fig. 1) show that the susceptibility decreases with increasing field, bringing into question the otherwise appealing description of liquid $^3$He as a "nearly-localized" solid.

The second method is based on the difference in the molar susceptibilities of concentrated and dilute liquid $^3$He. The difference makes it possible to separate the $^3$He atoms with an up-spin from those with a down-spin using fractional distillation in a counterflow of concentrated and dilute $^3$He. The procedure is performed in a 4He circulating dilution refrigerator, and a stationary polarization of 15% (seven times the equilibrium polarization in the 6.6 T field) at 14 mK has been obtained.

**Dilute gas cooling**

Dilute gas cooling — a fact, in fact, of atomic physics — has been actively studied by French groups, particularly this last decade. Gas atoms can be efficiently cooled by laser trapping and cooling (cesium vapour, for example, has been cooled to the μK range [6]). As a result, the hydrogen maser for a frequency standard has been improved considerably and more recently, a group at Harvard used a hydrogen maser to explore non-linearity in quantum mechanics.

A large international effort was devoted in the 1980's to Bose condensation in spin-polarized atomic hydrogen. An assembly of weakly interacting hydrogen atoms, polarized in a strong magnetic field, is a boson system since the atoms carry a total spin of zero or one (deuterium, on the other hand, obeys Fermi statistics due to its very large zero-point energy, spin-polarized hydrogen remains a gas all the way down to 0 K: it improves upon $^4$He and $^3$He which remain liquid (at moderate pressures). This, then, provides us with a unique opportunity to investigate Bose-Einstein condensation (BEC) in an interacting system of the well-documented interaction — of the rare gas type — can be largely modulated by changing the gas density.

Two different types of experiments have been carried out in this very challenging area [4]. Using extreme conditions (10 T, 0.3 K), very high densities (number of atoms per unit volume $n > 10^{19}$ atoms/cm$^3$) have been reached. However, efforts aiming at BEC failed due to relaxation and very energetic recombination processes so the high-density route is presently on stand-by.

Recalling that the Curie temperature $T_c$ varies as $n^{1/3}$, some groups turned to lower densities at mK temperatures or below. The evaporation of magnetically trapped atoms to cool hydrogen has been tested to a few mK; microwave traps have also been proposed. The breakthrough to BEC might in the end come from an optical scheme presently under investigation where spin-polarized hydrogen is laser cooled in a magnetic field trap using Lyman-α radiation.

**Adsorbed $^3$He**

$^3$He is well known from work on bulk samples that quantum tunnelling arises in solid $^3$He owing to the large zero-point kinetic energy of the particles with their small masses. The multiple spin exchange Hamiltonian (the most natural extension of the Heisenberg model) provides a very good description of the three-dimensional magnetization of bulk $^3$He by introducing the concept of exchange of rings of several particles (see G. Frosatti and N.F. de Oliveira, page 108). The exchange interaction between $^3$He atoms in two-dimensional systems should therefore lead to interesting effects.

The two-dimensional magnetics studied at the CR&TB consist of $^3$He layers which are adsorbed at low temperatures on an exfoliated graphite substrate (surface area of 50 m²). The sample, at about 1 mK, is located in a cell attached to a dilution refrigerator or a nuclear demagnetization stage; magnetic properties are most conveniently determined using NMR.

The density of adsorbed atoms can be adjusted to produce 2d systems in both liquid and solid phases, as well as in more exotic phases ("commensurate phases") due to the locking of the lattice parameter of the adsorbate to that of the substrate. Multi-layered are limited in thickness to about 10 layers by capillary condensation in the substrate.

A detailed investigation of the magnetic properties of these systems has been performed for a large coverage range with emphasis on the solid-like systems [5]. A multilayer with about 2.5 atomic layers displays an extraordinary ferromagnetism; the

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**Refrigerators for Special Applications**

The CR&TB's development of refrigerators for specific applications has focussed on miniaturisation, high vacuum operation, flexibility, and reliability. The first was a dilution refrigerator with much simplified operation, achieved by eliminating the $^3$He liquefaction stage using a heat exchanger to recuperate the enthalpy of the evaporating gas in the still. This resulted in a miniature device (now made under licence by the company TBT) of small diameter (29 mm) that can be rapidly cycled after sample changes; it is well adapted to magnetization measurements in large static fields (in collaboration with Nijmegen University).

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magnetic behaviour is determined by the second layer, a solid of triangular structure and relatively large lattice parameter where quantum exchange is particularly important. The magnetic susceptibility of this particular system is well described by the exact, high-temperature series expansion for the 2-d ferromagnetic Heisenberg Hamiltonian on a triangular lattice. The expansion does not diverge at any finite temperature in the measuring range, even at temperatures as low as 8 K (Fig. 2), where it is the Curie-Weiss temperature. This is the first time that agreement has been found between theory and predictions. The suppression of the ordering temperature predicted by Mermin and Wagner owing to the reduced dimensionality was clearly demonstrated.

Several other systems are presently being investigated, and there is convincing evidence that new experimental model systems for fermions on a lattice will soon be discovered. The 2-d Heisenberg antiferromagnet on a triangular lattice, studied extensively in recent years, is certainly a good candidate.

**Complex Systems**

Very different fields of research sometimes raise similar problems. So it is for fluid turbulence and glassy and glass-like systems. This is why we choose to present these fields in a parallel, and maybe provocative, manner.

**Turbulence**

Turbulence may appear as an exotic problem for low-temperature physicists. However, it touches the heart of their traditional preoccupations, both technical and conceptual. For instance, gaseous $^3$He is a very interesting fluid for studying strongly turbulent flows because its critical point at 5 K and 2 bars, lying near the regime where the kinematic viscosity is low, is particularly convenient. Reynolds numbers $Re$ at sub-metre scales can be increased spectacularly (using a jet one reaches $Re = 10^8$ with a nozzle of 2 mm in diameter) making an ordinary experimental vessel the equivalent of a wind tunnel. This, of course, calls for the evacuation of litres per minute of liquid $^3$He, and thus the handling $m^3$ per minute of gas at room temperature — standard practice for low-temperature laboratories.

The well-established hot-wire technique for velocity measurements can be improved using low-temperature approaches (e.g., micron and MHz resolutions are possible with superconducting films on a glass substrate). On the other side, turbulence raises fundamental problems in statistical physics, which is in turn traditionally linked to low-temperature research. For instance, we discuss below how the hierarchy of scales in turbulence could be similar to the hierarchy of time scales for relaxations in glasses and spin glasses.

**Disorder**

Disordered systems are undoubtedly encompassed by low-temperature physics owing to their unique properties. In the early 1970's, it was observed that structural disorder found in a few elementary insulating glasses induces specific properties at very low temperatures (below $1 K$). For example, as discussed on page 105 by P. Esquinazi et al., in contrast to the phonon Debye behaviour obeyed by crystals, "anomalous" acoustic or thermal properties arise as a consequence of disorder. There are "defects" with a broad distribution of characteristic energy extending down to very low energies, the effects of which can be observed at very low temperatures.

Two new groups of materials that are also characterised by some kind of disorder, or frustration, are found to exhibit "glassy" properties at very low temperatures. There are the quasicrystals characterised by a quasi-periodic structure in three dimensions which can accommodate a local,icosahedral symmetry. The origin of the new class of material to have been synthesised, show magnetic properties which are totally different to those for their crystalline (periodic) counterparts. Surprisingly, they undergo a spin-glass transition owing to a fraction of the Mn atoms retaining the full magnetic moment despite the presence of the Al matrix. The origin of the moment is still a matter of debate and work is needed to understand the quasicrystalline spin glasses. It is worth noting that the quasicrystalline spin-glass state is very similar to the one found in canonical crystalline Cu-Mn or Ag-Mn and that the Al matrix, its characteristics closely resemble those of the amorphous state. O. Rapp describes on page 104 quantum effects in transport properties of quasicrystalline $Al_{3}Cu_{3}Fe_{12}$ which are, on the other hand, much larger than those found in amorphous metals.

The second group comprises quasi-one-dimensional metallic compounds in which the electronic charge condenses below the Peierls transition into a charge-density wave (CDW). In its ground state, the CDW is pinned to the ionic lattice through the interaction with impurities or lattice defects: this disordered character is at the origin of metastable states and of several "glassy" properties of the CDW. At very low temperatures, properties characteristic of disorder are revealed such as a contribution to the specific heat (in addition to the phonon contribution below 0.5 K) with a smooth $T^x$ temperature dependence (with $x < 1$) and of the same order of magnitude as in glasses. The result confirms the universality of this thermodynamic property. More spectacular is the non-exponential energy relaxation occurring after a thermal pulse, or a thermal perturbation of long duration, has been sent into the sample. The kinetics of these long-time relaxations depend upon the time the perturbation was applied to the system — a phenomenon reminiscent of the relaxation of thermoremanent magnetization around the freezing temperature $T_f$ in spin glasses, and of aging effects below $T_f$. The effects of the time during which the system is maintained under external perturbation (magnetic field), in CDW materials, aging and a temperature decrease shift the spectrum of relaxation times of the metastable states towards very large values ($\sim 10^5 s$ or more at 100 mK; see Fig. 3).

**Possible connections**

There are possible and fruitful connections between disordered materials and turbulence which demonstrate the ubiquity of fundamental problems. In turbulent flows, the probability density functions (PDF) of velocity differences $V(x+r) - V(x)$ as a function of the position $x$ are strongly non-Gaussian for small distances $r$. But the PDF can be fitted by combining a Gaussian with a distribution $G_{\sigma}(r)$ of their variances $\sigma$. Similarly, the non-exponential energy relaxation in CDW materials can be fitted by combining exponential functions with a distribution $P(\tau)$ of characteristic times $\tau$. The
conducting ring where phase coherence is present, the quantum properties of the electronic wave-functions should be taken into account. The fundamental state is therefore sensitive to the fact that the flux inside the ring is not an integer multiple of the flux quantum \(\Phi_0\). Under these conditions, theory predicts a current circulating around the ring without any dissipation. This phenomenon is completely different from the current circulating in a superconductor ring because, in the normal state, the resistance of the ring is finite. Measuring this very small current in the \(\mu\)m-sized ring is extremely difficult. The magnetization created by the current created by 1000 magnetic spins, and represents a very small energy. In collaboration with the L2M laboratory at Bagnoux, France, we have developed a circuit comprising a ring of 3\(\mu\)m diameter, made in a GaAs-AlGaAs heterojunction, with a current-sensing SQUID of the same dimensions realised by electron lithography (Fig. 4). The device allows a very good coupling between the magnetization and current measurements. Results [7] show good agreement with theoretical predictions, in contrast to recent experiments at IBM and Bell Labs which gave a signal two orders of magnitude larger. New experiments with different samples are in preparation to understand the origins of the important discrepancy. The observed phenomena are not only reminiscent of, but complementary at a deep level to, the well-known Aharonov-Bohm flux quantization and localization effects. These have also been studied in detail using both normally conducting and superconducting artificial arrays of submicron size obtained by microfabrication techniques [8]. Resistance and magnetization measurements (made possible by the development at the ORTBT of specialized electronic instrumentation for low temperatures) show that the transition between normal conductivity and superconductivity does not vary monotonically owing to frustration effects induced by an applied magnetic field (Fig. 5).

Single-electron tunnelling
A spectacular manifestation of quantum effects at very low temperatures is single-electron tunnelling which has been observed recently in small tunnel junctions [9]. These fundamental experiments involve the controlled transfer of individual charges in semiconducting, metallic or superconducting islands through a series of tunnel barriers having capacitance below \(10^{-13}\) farads. The tunnelling channel, normally closed at mK temperatures when the Coulomb energy exceeds the thermal energy (Coulomb blockade), is opened in a controlled way by a small electrical bias on a gate electrode. This experiment bridges the current versus frequency gap in the famous metrology triangle, opening the principle of an independent measurement of the electronic charge. The other sides of the triangle are frequency/voltage and voltage/current, corresponding to other famous low-temperature effects (the Josephson and quantum Hall effects, respectively).

Future Developments
Low temperatures are, by necessity one might say, a very active field in fundamental research as well as in technology and instrumentation. Progress naturally requires an important theoretical effort. Numerical simulations are developing very rapidly, especially in the context of high-temperature ceramic superconductors (e.g., strongly-correlated fermions, 2-d Hubbard model, magnetic environment around vacancies). More generally, it seems that we are presently at a crossroads between the study of frustrated and disordered systems per se and progress in quantum coherence and quantum dynamics in these systems. This trend is, in itself, characteristic of progress in low-temperature physics and techniques.

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