Superfluid ^{3}He in the Zero-Temperature Limit

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Abstract

The properties of superfluid ^{3}He in the regime of negligible normal fluid density is both of fundamental interest and yet very simple. The behaviour is dominated by the properties of the condensate, and several phenomena, otherwise masked by the normal fluid, become observable. We discuss the techniques needed to cool the superfluid to $T \ll 0.1\, T_c$. We discuss some examples of the unique low Temperature behaviour; quasi-persistent spin precession, possible orbital precession, imaging turbulence, nucleation and the phase diagram in aerogel.

Key words: superfluid; Helium-3; refrigeration; ultralow temperature

1. 1.Introduction

The quantum fluids are the celestial spheres of low temperature physics; condensed materials with the most austere perfection and simplicity. Our working roadmap of these unique liquids, the two-fluid model, embodies the idea of the flawed perfection of the ideal superfluid contaminated by the unruly normal fluid. Much of our understanding of the liquids concerns the interplay of these two components. The helium superfluids have complementary properties: ^{4}He consisting of 'hard' atomic bosons has only mass to characterize its coherent behaviour, while the Cooper pair 'soft' bosons of ^{3}He have mass, nuclear spin and orbital momentum, each with its own coherence and to some extent its own associated superfluid. It is our purpose in this paper to address the latter material and to direct attention to the regime where the normal fluid contamination is negligible and we begin to glimpse the properties of the 'bare' liquid ^{3}He condensate.

Currently we can cool the superfluid to T_c/T of around 13 (see below). At these temperatures we can confidently say that there are *no* impurities in the bulk liquid. The only impurity possible in liquid ^{3}He is dissolved ^{4}He. From higher temperatures we know the solubility follows the form $T^{-3/2} \exp(-\epsilon/k_B T)$, with ϵ the phase separation scale energy of around 0.8K. At our lowest temperatures this yields a ^{4}He solubility of order 1 in 10^{3000}. That requires a 10^{1000} light year cube of superfluid ^{3}He before we have a chance of finding one dissolved ^{4}He atom.

At the lowest temperatures the number of unpaired ^{3}He atom quasiparticles in the liquid is also negligible. At the lowest temperatures which we can measure there are about 10^{12} unpaired atoms per cubic cm, corresponding to the density of a room temperature gas at $\sim 10^{-6}$ bar. At these temperatures the $\exp(-\Delta/kT)$ Boltzmann factor is so steep that a factor of two reduction in temperature would give a density of only one quasiparticle per cubic cm, in other words to a regime where macroscopic volumes of the liquid are quasiparticle-free for large fractions of the time.

2. Cooling to the 'Zero Temperature' Regime

A combination of dilution refrigeration and nuclear cooling will readily cool copper refrigerant to a few tens of microkelvin[1]. The difficulties come when we connect the refrigerant to the liquid, and confine the liquid in a container. We have to cool liquid helium via an immersed volume of sintered metal. Our configuration

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of a stack of copper refrigerant plates each coated on both sides with a layer of sintered silver acts as a virtually perfect getter for quasiparticles. Any quasiparticle penetrating into the labyrinthine sinter surfaces has a very low probability of emerging again. If we apply a 1000 pW quasiparticle flux to one end of such a stack, nothing emerges from the far end.

The absorption of the quasiparticle flux by the sinter must balance that generated by the incoming heat leak. With good design we can minimise the external heat input down filling tubes, and so forth. The troublesome source is the internal heat leak from the materials of the container, which is strongly material-dependent. Metals are clearly best since they come rapidly into internal thermal equilibrium and should not leak heat into the liquid over long periods of time (apart from the initial 'time-dependent heat leak'). Epoxy materials with unhygienic properties are much worse. A square cm of epoxy leaks of order 1 pW continuously into liquid ^{3}He in contact. We therefore avoid too much plastic, which is a pity as epoxy is easy to fabricate and not subject to eddy currents. If we wish to use magnetic fields we can make critical parts of sapphire, but this is far from ideal from the fabrication point of view.

At the low temperatures the rare quasiparticles are non-interacting. We can therefore picture the ^{3}He sample as carrying a wind of quasiparticles which travel ballistically from the material of the cell walls until they strike cooling sinter where they are absorbed. Despite the lack of a thermalisation mechanism in the bulk liquid, we know that the temperature is a meaningful quantity[2]. We believe that the higher density of surface quasiparticle states associated with the depressed energy gap at the walls are in good thermal contact with the wall material. The bulk quasiparticles have a thermal distribution in equilibrium with this layer.

Designing a cell for the lowest temperatures is thus simply a matter of minimising the external heat leak, reducing unhygienic materials to a minimum, keeping them out of direct line of sight of the experiment, maximising the sinter volume, and surrounding the experimental volume with it. Fig. 1 shows a current Lancaster double cell. The outer volume is filled with 1 mm Cu plate refrigerant coated with 1 mm thick sintered Ag powder, surrounding an inner cell with ~0.1 mm Cu plates thinly coated with Ag sinter. Between the inner and outer cells is a separate filling tube and thermal heat switch. When such a cell, filled with liquid ^{3}He at zero bar, is precooled to 4.5 mK in a field of 7 T, demagnetization to 100 mT will leave the outer cell below 200 μK and the inner below 80 μK. The tower shown is designed for NMR but a similar double structure, in fields up to 0.5T can be used to stabilise a low-temperature A-B interface.

This configuration is sufficient to cool the liquid to temperatures lower than we can measure, rendering more elaborate cooling arrangements unnecessary. A more extreme cell for use at the lowest possible temperatures for dilute solutions and with the experimental volume completely shielded by several layers of silver sinter is currently in use by the Helsinki group[3].

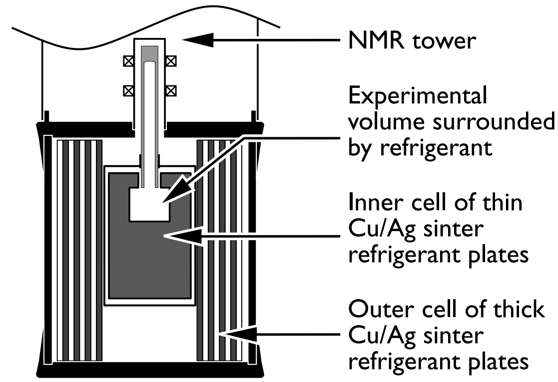

Fig. 1. A contemporary Lancaster double cell.

For thermometry we invariably use vibrating wire resonators (VWRs) in various parts of the cell. A VWR immersed in a quasiparticle gas in the ballistic limit yields a frequency width proportional to the gap Boltzmann factor, $\Delta f_2 \propto \exp(-\Delta/kT)$. Thus a measure of the frequency width Δf_2, either directly by sweeping the resonance line or indirectly by measuring the amplitude on resonance, yields the temperature directly to very high accuracy[4].

3. The Regime of ~Zero Normal-Fluid Density

3.1. *Quasi-persistent Spin Precession*

Persistent currents are unique to superfluids. In superfluid ^{4}He and ^{3}He-B, superflow persists, being decoupled (at modest velocities at least) from the dissipation of the normal fluid. In ^{3}He we also have the quasi-independent spin and orbital liquids. The magnetic behaviour of the spin liquid is non-persistent since the superspin and normal spin components experience the same local magnetic field and the normal dissipative spin fluid acts as a drag on the superspin component. Thus the free induction decay after an NMR tipping pulse, albeit much longer than that in the normal state, decays with time since both components contribute and dissipation in the normal component is shared.

Thus to see true persistent magnetic behaviour we need to remove the normal component, i.e. work at the lowest temperatures. The results are spectacular. For example under circumstances where the precession induced by an NMR pulse would decay in a few millisec-

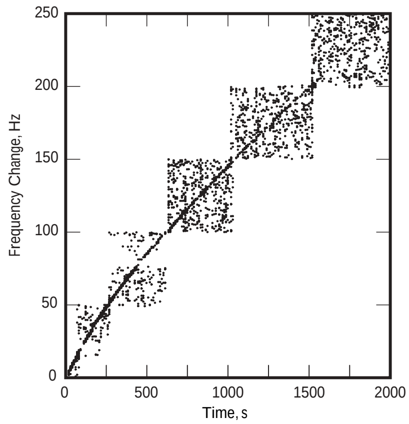

Fig. 2. The evolution of a quasi-persistent precessing mode as seen in the free induction decay. The precession can be followed for more than half an hour.

onds in the normal fluid, at our lowest temperatures we can follow the decay over half an hour[5]. The precessing structure in the superfluid is held in a rigid coherence by several subtle quantum feedback mechanisms which minimise gradients in the spin part of the wavefunction. This behaviour at higher temperatures is impossible to follow (or even induce) owing to the drag from the normal spin fluid. A ring-down of 2000 seconds at a frequency of 1 MHz implies a Q-factor for the quantum coherence of $\sim 10^9$.

However we believe we also see the beginnings of orbital precession. When a magnetic field is applied to the B-phase the symmetry of the superposition of the +1, 0, -1 components of S and L is lifted, and a small net spin and orbital value appears. The appearance of a small L component is associated with a distortion of the gap giving a depression along L. This depression fills with a pool of low energy excitations. If L, and thus also the gap minimum, is forced to precess, as shown in Fig.2, excitations are forced up in energy. The accompanying entropy production gives rise to the 'orbital viscosity' which at higher temperatures ensures that the direction of the L-vector is clamped.

However, in our almost quasiparticle free regime this mechanism is no longer operative and we should begin to see the behaviour of an 'orbital' superfluid along with an associated orbital superflow. This would be a completely new phenomenon. The influence of orbital precession might well show up first in NMR where the precession of the S vector generated by NMR should begin to drag the L vector with it. We believe the long-lived precessing structures with relatively low amplitude must rely on sympathetic precession of the orbital component which increases towards the transverse boundary of the domain to allow the precession to lock at a single frequency across the structure[6].

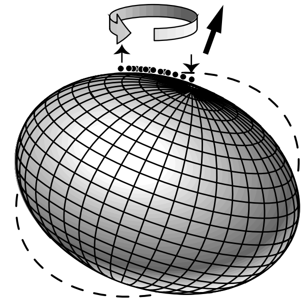

Fig. 3. Orbital viscosity. In a magnetic field, precession of the L vector and associated gap distortion, constantly redistributes the quasiparticle gas in the gap minimum. This is a dissipative process which at high T clamps the direction of L.

3.2. *Quasiparticle-Illuminated Turbulence*

Quantized vorticity is superfluid ^{3}He provides our strongest analogy to the metric of the Universe. Analogies have already been drawn experimentally and theoretically between the creation via the Kibble mechanism of both cosmic strings and quantum turbulence[7][8]. In ULT superfluid ^{3}He-B, we find that the tenuous quasiparticle gas provides the illumination by which we can see the temporal and spatial evolution of quantum turbulence by its effect on a nearby vibrating wire resonator. As shown in fig. 4, vortices can shield the wire from excitations incoming from infinity which have to traverse the vortex flow field. The flow field introduces a Galilean shift to the quasiparticle energies which may cause Andreev reflection of incoming excitations before they reach the wire. If the flow field is such as to reflect quasiparticles, then incoming quasiholes can pass. However, after scattering half of the excitations are again Andreev reflected, return to the wire, to be scattered again. Thus the flow field restricts the number of excitations with energies within $v_{\rm flow}{\cdot}p_F$ of the gap which can scatter with the wire and carry away momentum. Thus the presence of vorticity reduces the damping of the wire from thermal excitations. In other words the wire sees the 'shadow' thrown by the vortex in the thermal excitation 'illumination'. This single-pixel 'image' of the turbulence has turned out to be a very powerful tool in investigating the fluctuations, temporal and spatial evolution of turbulence in superfluid ^{3}He[9]. Further refinements with arrays of pixels and directed thermal beams of illumination should allow us to make recognisable two-dimensional images of vorticity, a valuable advance in the understanding of (quantum) turbulence.

3.3. *Phase Boundaries and Nucleation*

That superfluid ^{3}He may exist in several phases is also of great interest. We have spent considerable effort

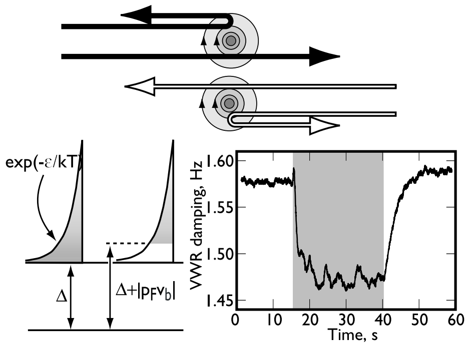

Fig. 4. When vorticity surrounds a VW resonator incoming quasiparticles can be Andreev reflected by the associated flow field. Outgoing excitations can also be trapped until undergoing an Andreev reflection. These excitations do not exchange momentum with the wire. The vorticity thus throws on the wire a shadow in the thermal-excitation illumination and the damping decreases, allowing the vorticity to be visualized. At bottom right we see that vorticity, generated during the grey period, reduces the damping but increases the fluctuations.

in looking at the thermodynamics and surface tension of the phase transition/interface[10][11]. The really interesting fundamental behaviour is the nucleation of one phase from the other, since in the very low temperature regime this is a transition from one virtually 100% ordered phase to another. The influence of thermal fluctuations becomes negligible since the enthalpy of both phases is virtually zero. In consequence we are currently looking for evidence of tunnelling-mediated phase transitions.

3.4. *Aerogel*

Immersing the liquid ^{3}He in aerogel is the conventional way of introducing disorder into the system. In the low temperature regime we can make two observations on this subject. First, although we believed that the aerogel might well influence differently the A and B phases and thus distort the $B-T$ phase diagram, surprisingly the $B-T$ phase diagram for the liquid in aerogel has the same form as in the bulk, with the transition temperature T_{AB} and the A-B transition field B_{AB} depressed by precisely the same factor, see fig. 5. Whatever aerogel does to the superfluid it seems to do it in a very straightforward way[12].

The depression of the superfluid transition temperature by immersion in aerogel brings a new lease of life to our low temperature thermometry. The sensitivity of our VWRs only extends to temperatures where the quasiparticle damping ($\propto \exp(-\Delta_{\mathrm{bulk}}/kT)$ exceeds the internal wire damping. This cuts in at around $T_c/T \approx 10$. However, if we add a block of aerogel to the resonator the increased normal fluid density in the aerogel influences the mass of liquid taking part in the backflow, changing the frequency of the wire. This effect is governed by the aerogel gap factor $\exp(\Delta_{\mathrm{aerogel}}/kT)$ which can be orders of magnitude larger than that in the bulk liquid. An aerogel loaded resonator can thus extend our temperatures measurement in the bulk down to T_c/T approaching 15.

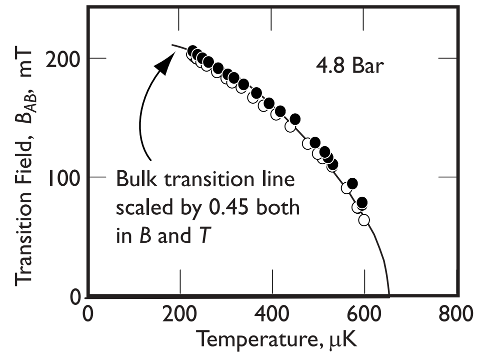

Fig. 5. The A-B phase transition at 4.8 bar in 98% aerogel. A single factor scales the transition line from the bulk behaviour.

The simplicity of the condensate-alone regime makes it an ideal laboratory for investigating many problems in condensed matter physics under ideal conditions, of which phase transitions and interfaces, turbulence and cosmological analogues with the metric of the Universe are current hot topics.

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