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Superfluid ^{3}He in the zero temperature limit

(Review Article)

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In this paper we discuss some (and only a small fraction) of the interesting properties of superfluid ^{3}He at the low temperature limit. We concentrate on the unique behaviour and applications of the very dilute excitation gas at the lowest temperatures. This gas has been used for among other things, the probing of the *A–B* phase interface, the detection of low energy particle events and in the simulation of the creation of cosmic strings.

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Introduction

We can think of the classes of quantum fluids as existing in a distinct hierarchy of complexity. The simplest is superfluid ^{4}He. Here the starting material of the condensate, the ^{4}He atoms are bosons. They have no spin, no charge and are spherically-symmetrical filled-shell noble gas atoms. In the condensate they offer no labels other than their mass. Thus the superfluid component in liquid ^{4}He has a wavefunction which gives information only on the distribution and motion of the mass in the system. A distortion of the wavefunction may therefore generate a response only in terms of mass, in this case a mass superflow.

The next more complex system in our hierarchy is the superconducting electron gas in a conventional superconductor. Here the component particles, the electrons, are fermions and may only contribute to a boson condensate by coupling in Cooper pairs. Here we have the possibility of more structure since a pair may have orbital and spin angular momentum. However, in conventional superconductors at least, the Cooper pairs choose the simple solution and couple with spins opposed. The total spin is thus zero, and to maintain the correct symmetry the orbital angular momentum must be even, and also takes the value zero. The Cooper pairs in a superconductor are thus also very simple. They carry mass, and more importantly charge. Therefore a distortion of the wavefunction can lead to a supercurrent (the associated mass current is unimportant in comparison). In more exotic forms of superconductivity, where the pairs may have nonzero spin the situation could in principle be much more complex. The fact that the Cooper pairs carry a charge couples the condensate into electromagnetism yielding all the exotic quantum-electrical properties for which the superconductors are valued. Further, on the mundane practical level, this means that we can examine superconductivity by including the superconducting element under examination in a simple electric circuit. Our measurement of the current and voltage then allows us to infer what is happening inside the superconductor. Direct observation of the superconducting behaviour in situ is much more difficult.

The third class in our hierarchy is exemplified by superfluid ^{3}He. Here the starting particles are again fermions, the ^{3}He atoms which carry a nuclear spin. However, in this case the coupling of the pairs yields, not zero spin, but spin 1. To maintain the correct symmetry the pair angular momentum must be odd and in fact in the ground state is 1. Therefore the Cooper pairs comprising the condensate are characterized by mass, nuclear spin and orbital angular momentum. This a) makes for a much richer structure and b) allows us to examine the very essence of the superfluidity by providing us with a window into the internal structure of the condensate itself by NMR.

The low temperature regime

Experimentalists working with quantum fluids generally think about the subject in terms of the two-fluid model, the interplay between the normal fluid and superfluid components being one of the characteristic features of these unique systems. However, near zero temperature we have a new regime. The normal fluid density is negligible and we are left with «pure» superfluid. In the case of superfluid ^{3}He this turns out to be a very rewarding region since the condensate itself has such a rich structure. In fact, the behaviour turns out to be increasingly interesting as the disturbing interference of the normal fluid is removed with falling temperature.

Some of the most arresting properties of the quantum fluids remain the persistent phenomena, persistent mass flow in superfluid ^{4}He and persistent currents in the superconductors. In superfluid ^{4}He the normal fluid and superfluid components are coupled together via the mechanism known as mutual friction. Since the normal fluid flow is dissipative this coupling acts to prevent persistent flow in the superfluid in the general case. (The process is mediated by vortices which carry a circulation of 2π of wavefunction phase around the vortex axis. If a vortex can cross the path of the superflow then 2π of phase is either added or removed from the phase gradient thus mediating the decay of the flow.) To see real persistent flow phenomena in superfluid ^{4}He, we must either restrict ourselves to low flow velocities or make experiments in very restricted geometries which inhibit the flow of vortices. In the superconductors, on the other hand, the normal and supercurrents are almost completely decoupled and persistent currents in loops can be maintained for very long periods. Which of us has not been impressed when as students we learned for the first time that currents could be maintained circulating in loops for periods of many years?

The properties characteristic of, and unique to, superfluid ^{3}He at the very lowest temperatures are associated with the magnetic behaviour of the nuclear spins and with the dilute gas of residual thermal excitations. Unfortunately, magnetic interactions are long range and during dynamic motion of the spin system, say after an NMR pulse, the magnetizations associated with the normal and superfluid components are very tightly coupled. Under certain circumstances these can be separated [1] but this is the exception. The possibility of persistent magnetic phenomena is very interesting. The only straightforward means to observe such behaviour is to resort to very low temperatures where the dissipative effect of the normal fluid is so weak as to be negligible on the time scale of an experiment. We cannot reach this regime yet, but we have approached close enough that persistent behaviour of several minutes can be observed, giving us a tantalizing insight into what might lie in store for us at lower temperatures. At temperatures close to zero the quasiparticle excitations above the ground state form a fascinating dilute gas. Since the excitation dispersion curve is of the «double minimum» BCS type, the dynamics of the particles is very unlike that of a conventional «Newtonian» gas where the dispersion curve is the familiar, $E = p^2/2m$, parabola. This leads to many non-intuitive properties as we discuss below.

These two low temperature properties of superfluid ^{3}He are those which have attracted most of our interest at Lancaster. In collaboration with Yuri Bunkov formerly of the Kapitza Institute and currently working in Grenoble, we have been studying the magnetic properties of the condensate at the very lowest temperatures through NMR. However, what we are concerned with in this paper is the unique behaviour of the extremely dilute gas of the quasiparticle excitations. This gas not only has very unusual properties in its own right, but also provides a convenient probe for studying other properties of the superfluid. In this context, we have been examining the thermal behaviour of the superfluid which we believe can be used as a very sensitive particle detector. Finally, jointly with CRTBT, Grenoble we have been exploiting the particle absorption techniques developed earlier for studying the simulation of cosmic strings creation, via the Kibble mechanism, by looking at the formation of vortices after a sudden crossing of the superfluid transition.

The excitation gas

We start by considering the properties of the very low temperature excitation gas. This is one of the few in nature in which an entire assembly of particles with non-Newtonian dynamics is completely accessible. There are similar ensembles of excitations in condensed matter physics, but almost all are trapped in a lattice. The ^{3}He excitation gas is contained only in a superfluid condensate, which for most mechanical purposes can be treated as a vacuum, and the independent dynamics of the excitations can be studied. This is especially the case at low temperatures, where the low excitation density ensures that collisions are rare and the excitations behave entirely ballistically.

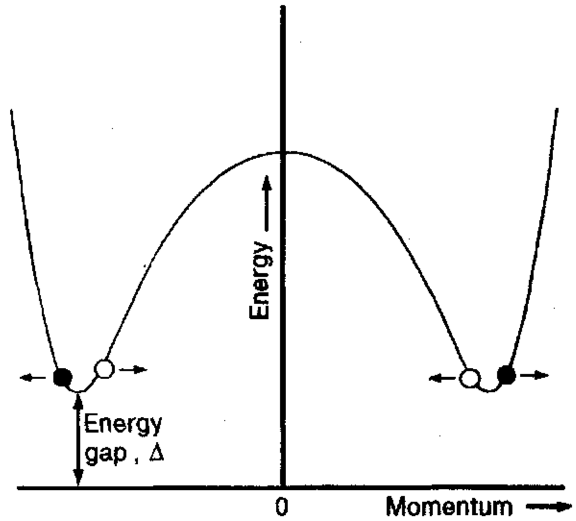

Fig. 1. The excitation dispersion curve in superfluid ^{3}He. The minimum is the curve comes not at zero momentum as for a conventional Newtonian object but rather at the Fermi momentum. This means there are two classes of excitation; quasiparticles (filled circles) with momentum and velocity parallel and quasiholes (open circles) with momentum and velocity opposed.

The unusual behaviour of the quasiparticle excitation gas is a result of the double minimum dispersion curve shown in Fig. 1. This curve is quite different from the Newtonian parabola in having the energy minimum not at zero momentum but at the Fermi momentum. Furthermore, this leads to two different types of excitation: quasiparticles with group velocity and momentum parallel and quasiholes with group velocity and momentum opposed. The gas has rather different properties in the two phases of superfluid ^{3}He. However, in the B-phase the excitation curve is virtually isotropic and the energy gap to the excitation energy minimum is the same in all directions. The curve of Fig. 1 holds also for the A-phase but in this case the gap is dependent on the direction relative to the direction of the Cooper pair angular momentum, with two polar nodes of zero gap and a maximum gap around the equator.

In the B-phase the energy gap to the minimum excitation energy implies at low temperatures an excitation density dominated by the gap Boltzmann factor exp $(-\Delta/kT)$. At the lowest accessible temperatures (around 100 μK at zero pressure) the density of excitations is vanishingly small, the number of unpaired ^{3}He atoms being of the order of 1 in 10^7. The mean free paths of the excitations are therefore very long, orders of magnitude longer than any experimental dimension. Thus we may carry out experiments with beams of excitations.

Near the minimum in the dispersion curve it can be seen that an excitation may have its group velocity reversed for a negligible change in momentum. This is the so-called Andreev reflection in which a quasiparticle (quasihole) incident on a region of increasing gap is reflected as a quasihole (quasiparticle). This process was first discussed by Andreev in the context of electron reflection at a normal-superconducting interface. However, in the superfluid ^{3}He context such reflection processes have a very strong influence on the dynamical properties, since they permit an excitation to be reflected with virtually no change of momentum.

A further interesting aspect of the dispersion curve of Fig. 1 is the fact that it is not invariant but may be changed. When we move relative to the superfluid ^{3}He, unlike in a normal gas the excitation dispersion curve in our frame of reference takes up a different shape. While we move, excitations with momenta approaching are seen to have increased energies and those with momenta receding have decreased energies. For a Newtonian particle this simply translates the energy/momentum parabola. In the superfluid ^{3}He case, however, the excitation dispersion curve becomes canted as shown in Fig. 2. The effective gap for approaching excitations increases and that for receding excitations decreases.

The vibrating wire resonator

We can make use of these properties of the dispersion curve to create a very sensitive mechani-

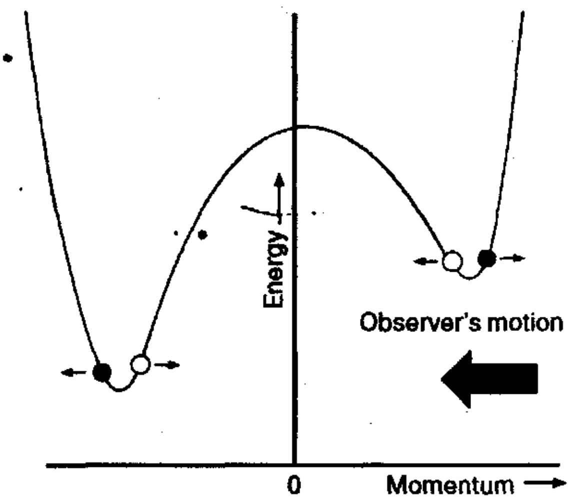

Fig. 2. When observed in a moving frame the dispersion curve of Fig. 1 is seen to be canted. Excitations with momenta directed towards the moving observed have higher energies in this frame and those with momenta directed away have lower energies.

cal quasiparticle detector. The device we use is a vibrating wire resonator which is a simple semicircle of very fine superconducting wire, as shown in Fig. 3. The loop has a mechanical resonance in which the wire moves perpendicularly to the plane by the flexure of the wire legs. If the loop is placed in a magnetic field, as shown, then a current at the appropriate frequency through the wire will set it into oscillation from the Lorentz force on the current. The motion of the loop through the field sets up a voltage across the loop (from the cutting of the field lines) which we can monitor to infer the velocity. From this simple device we can infer the behaviour of the excitation gas from its damping effect on the motion of the resonator. We sweep the frequency through the mechanical resonance of the wire loop and measure the width at half height of the in-phase signal, Δf_2.

Since the density of the excitation gas at the lowest accessible temperatures is comparable to that of a moderately good vacuum, one might suppose that a mechanical method of detection is unlikely to be very effective. Paradoxically, quasiparticle excitations produce a very large mechanical effect on such a resonator. First, from the shape of the dispersion curve, the excitations have very large momenta for their energies compared to «conventional» excitations. Furthermore, when the wire is moving through the excitation gas the dispersion curve in the frame of the wire becomes canted as discussed above. This has a large effect on the dynamics of the response of the gas to the motion of the wire. The situation is illustrated schematically in Fig. 4. The canted dispersion curve has the effect that for quasiholes approaching the wire from the forward side there are no outgoing hole states with

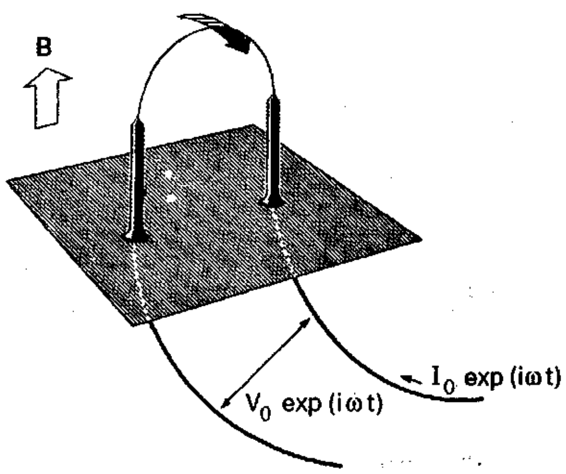

Fig. 3. A vibrating wire resonator.

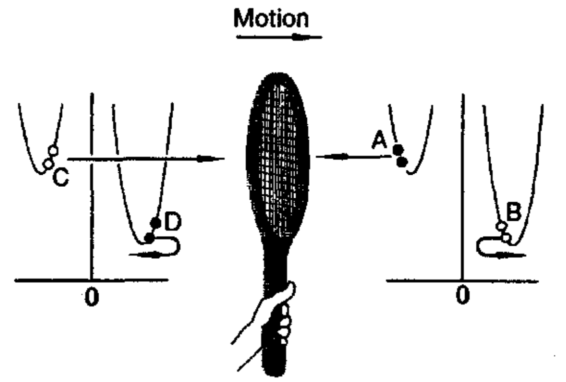

Fig. 4. A schematic diagram of an object moving through superfluid ^{3}He-*B*. For simplicity, a tennis racket is used as the representative object since this may be assumed not to displace the condensate, but only reflect the excitations. In the rest frame of the moving racket (in which scattering is elastic) we see that, for excitations approaching from the front, only quasiparticles (filled circles) may be normally reflected. Quasiholes must be Andreev reflected with virtually no exchange of momentum with the racket. The converse holds on the rear side. This multiplies the force on the racket by several orders of magnitude over that expected for a similar «conventional» excitation gas.

similar energies and the quasiholes must be reflected by Andreev processes and thus exchange negligible momentum with the wire. Similarly quasiparticles approaching from the rear must also be Andreev reflected. This has the effect that even at modest velocities normal scattering processes are biassed to give a preponderance of quasiparticle scatterings on the forward side and quasihole scatterings on the rear side. Both these processes impede the motion of the wire.

This has two effects, first the resistive force opposing the motion of the wire becomes a constant, independent of velocity, above a velocity of $v = kT/p_F$ [2] which is quite unlike the behaviour in conventional gases. This can be seen in Fig. 5 where we plot a typical force-velocity curve [3]. Furthermore, at more modest velocities there remains the imbalance of scattering processes of the quasiparticles and quasiholes which amplifies the damping effect of the excitations on the wire by many orders of magnitude over the effect of a conventional gas of particles with similar energies [2]. Taking all these factors into account, we find that the density of quasiparticle excitations in the superfluid is very easy to detect by mechanical methods even at the lowest temperatures.

At low velocities, if we do the full calculation [2], the damping turns out to be proportional to the gap Boltzmann factor, $\exp(-\Delta/kT)$. This means

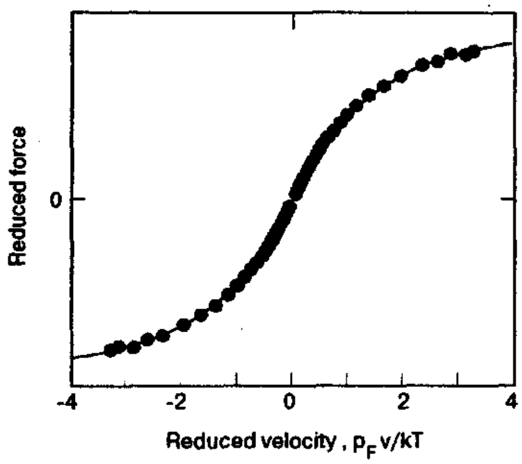

Fig. 5. The measured force–velocity curve for an object moving in the excitation gas. The velocity-independent force above a velocity of $v = kT/p_F$ is quite apparent.

that we can simply calculate the width from the known properties of the wire resonator and the temperature. However, we have measured the damping against an NMR temperature scale as shown in Fig. 6. This measurement was made many years ago [4] and confirmed the exp $(-\Delta/kT)$ dependence of the damping. This variation of damping with temperature provides us with a very accurate thermometer for the lower temperature regions, since exp $(-\Delta/kT)$ changes so rapidly with temperature. For example, there is a change of a factor of 16 between 100 and 120 μK for the *B*-phase at zero pressure.

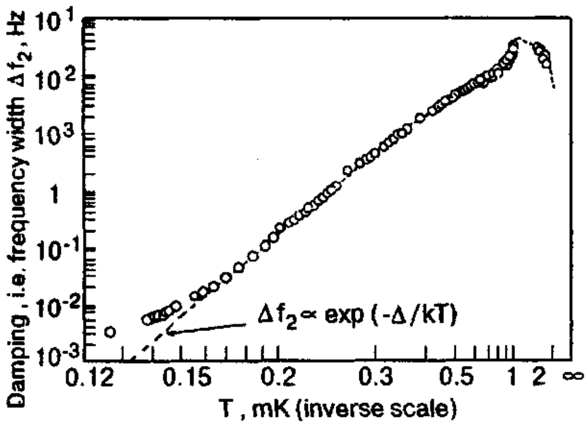

Fig. 6. The frequency width, Δf_2, of a vibrating wire resonator plotted as a function of temperature as measured by Pt NMR. This is very old data and is rather poor at the lower temperatures where the damping becomes very small and we have to measure for many hours to determine the frequency width. More modern resonators are made of much thinner wire, giving a larger damping which is much easier to measure.

Quasiparticle beams

In recent years we have extended our interest to examining the behaviour of quasiparticle beams. To do this we need a spectrometer which implies both a quasiparticle beam source and a quasiparticle beam detector. The device we currently use was developed by Fisher [5] at Lancaster. This is essentially a black-body radiator for quasiparticles. The device consists of a box immersed in the superfluid *B*-phase with a small hole in one wall, as shown in Fig. 7. Inside the box are two vibrating wire resonators. One acts as a thermometer to measure the temperature (or quasiparticle density). The other acts as a heater and makes use of the following principle. If a resonator is driven at high enough velocity the liquid can be locally accelerated above the Landau critical velocity for pair-breaking. Beyond this velocity the moving wire can create a shower of excitations both quasiparticles and quasiholes. In other words, we can use a heavily-driven resonator as a heater. Such a heater has the great advantage that the heat is generated directly in the liquid. This is important, since at the lowest temperatures the Kapitza conductance between the superfluid and solid heater is so poor that thermal contact is too weak for a well-defined quantity of heat to be emitted into the liquid.

The black-body radiator is thus a small enclosure of around 0.1 cm^3 volume continuing a heater and thermometer. The device can be used in both detector or emitter mode. When used as a detector the flux of excitations incident on the hole can be deduced from the temperature rise inside the enclo-

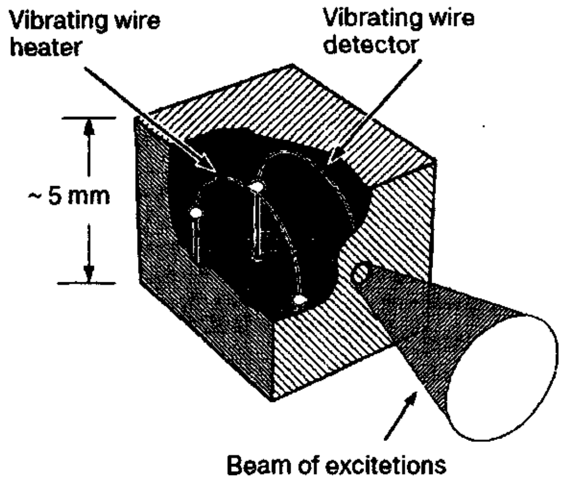

Fig. 7. A quasiparticle black body radiator. The box contains a heater and thermometer vibrating wire resonator. When heated a beam of thermal excitations (quasiparticles and quasiholes) is emitted from the small hole.

sure. In emitter mode heat is introduced into the liquid in the enclosure by the heater. This generates a flux of excitations leaving the small hole. The flux of excitations leaving the hole is determined by the temperature inside, T, and is given by

$$\dot{n} = A\,kT\,\exp(-\Delta/kT)$$

where A is a constant. (For simplicity in presenting the argument here, we assume that the temperature of the superfluid outside the enclosure is zero.) Since the excitations emerge with a thermal distribution of energies the mean energy is simply $\Delta + kT$ and the energy flux can thus be written:

$$W = A\,kT\,(\Delta + kT)\,\exp(\Delta/kT)\,. \qquad (1)$$

To calibrate the radiator as a quasiparticle source we need to determine the value of A. This we do by applying a steady energy input to the liquid via the heater resonator and observing the temperature inside. If we plot the values for equation [1] for such a calibration we find the experimental fit is linear over many orders of magnitude of input heater power. Furthermore, the lowest detectable power is of the order of 10^{-16} Watt or below [6], which means, as we shall see below, that these devices can be used as particle detectors.

Beam experiments; direct observation of Andreev reflection

We have made a number of experiments with such devices. The two easiest to understand are that designed to allow the direct observation of Andreev reflection and that designed to probe the A-B phase interface, since these experiments need only a source radiator. For the observation of Andreev reflection we set up a radiator which had a small paddle in front of the hole from which the thermal beam is emitted. The setup [6] is shown in Fig. 8. If we move the paddle towards the hole then the backflow around the paddle ensures that the quasiparticles leaving the radiator find that states near the paddle have their energies decreased (since the liquid is approaching the emitted beam) while quasiholes find their energies increased. This means that quasiholes in the beam are Andreev reflected by the velocity gradient and are returned along the line of the beam back into the radiator. (A feature of Andreev reflection is the almost perfect reversal of the group velocity of the excitation so reflected.) The situation is illustrated in Fig. 9. Since a fraction of the emitted beam is thereby returned to the radiator the excitation density inside is increased above the density observed when the paddle is stationary and there is no Andreev reflection. From the temperature rise we can in principle calculate the fraction of the beam Andreev reflected. In practice the paddle cannot be moved steadily towards the radiator indefinitely but must be oscillated back and forth. The fraction reflected must therefore be integrated over a complete cycle of the motion of the paddle. When this is done, the rise in

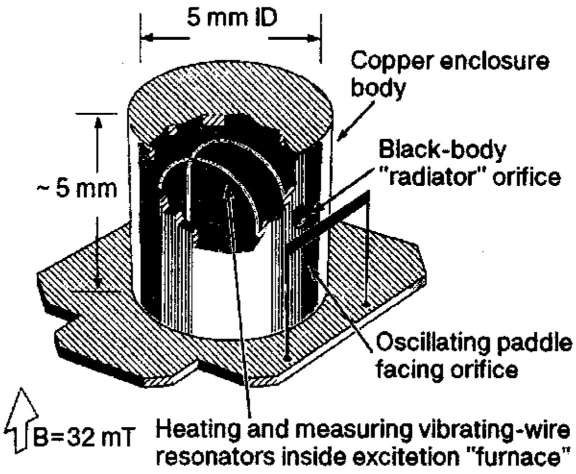

Fig. 8. The experiment to observe directly Andreev reflection. An oscillating paddle faces the black-body radiator beam orifice. When the paddle is moved the velocity field around it causes Andreev reflection of excitations back into the radiator and the temperature inside thus rises.

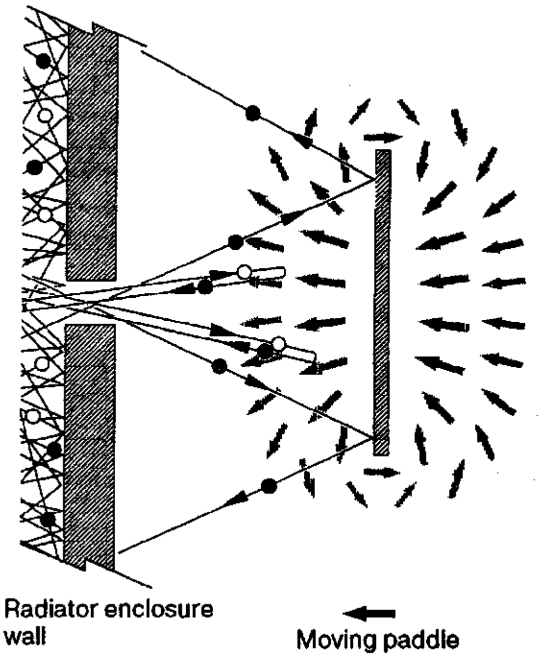

Fig. 9. A schematic diagram of the Andreev experiment. The flow around the paddle causes Andreev reflection of excitations (in the case illustrated the quasiholes are reflected). Since Andreev reflection is an accurate retroreflection process the reflected excitations return to the radiator enclosure.

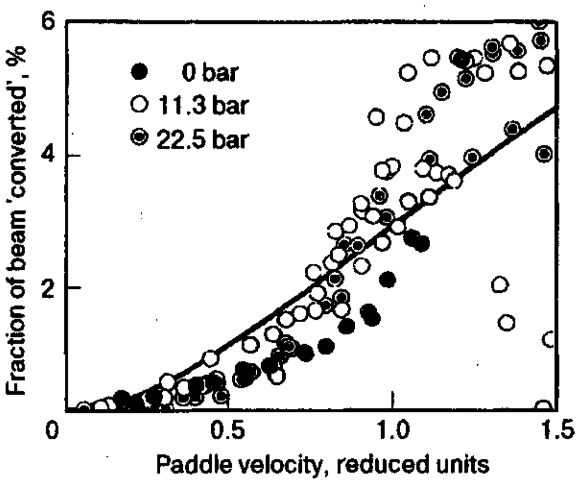

Fig. 10. The measured fraction of excitations reflected by Andreev processes in the black body radiator and paddle experiment as discussed in the text. The solid line represents a theoretical estimate using a simple one-dimensional model.

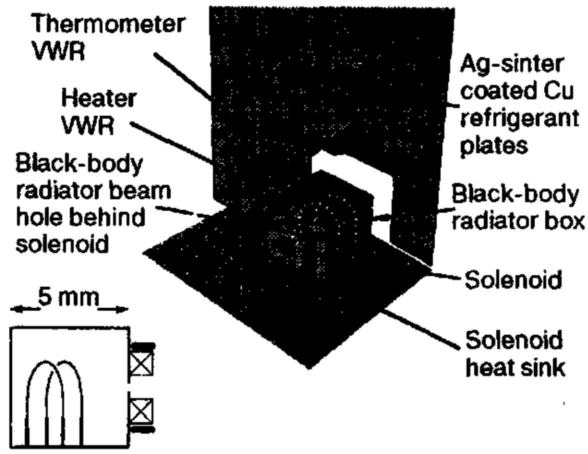

Fig. 11. The experiment used to probe the superfluid ^{3}He *A-B* phase interface. A black-body radiator has a small solenoid surrounding the beam hole. This may be used to create a phase interface across the beam (see text).

temperature inside the box is found to be in good agreement with a simple one-dimensional model of the behaviour [6]. A plot of the fraction of excitations Andreev reflected as a function of paddle velocity is shown in Fig. 10, along with a calculation of the expected behaviour as discussed in reference [6]. This experiment constituted the first direct observation of Andreev reflection in superfluid ^{3}He and provided a much less equivocal result than similar experiments made in superconductors.

Beam experiments; probing the *A-B* phase interface

For the experiment to probe the phase interface between the two superfluid phases, the *B*-phase and the *A*-phase, we stabilized a small region of *A*-phase liquid by applying a very localized magnetic field [7]. The region was arranged to be directly in front of the beam hole of a black-body radiator, as shown in Fig. 11. In this case the actual gaps in the liquid are changed by the magnetic field. In the *B*-phase the gap is decreased along the direction of a magnetic field, but the excitation spectrum is split according to whether the spin is parallel or antiparallel to the field. The parallel gap in the *A*-phase is 15% larger than the undisturbed gap in the *B*-phase. We can measure these gaps since we have set them up along the beam trajectory. Excitations approaching the region of increasing gap must be Andreev reflected when the effective gap becomes equal to the excitation energy. The excitation is thereby returned to the radiator increasing its temperature. A measurement of the temperature in the radiator as a function of magnetic field along the trajectory gives us the value of the maximum gap along the beam. Since in the *B*-phase the gap change depends on the spin value we have to split the calculation into two parts for the *B*-phase part of the problem. Thus we can measure both the maximum *B*-phase gap as a function of field and the *A*-phase gap in the same experiment, again by exploiting the unique properties of Andreev reflection. The measured gaps, as shown in Fig. 12, turn out to be in good agreement with accepted values. However, the maximum gaps in an excitation spectrum have not been readily measurable earlier. In usual spectroscopic methods the minimum gap tends to dominate the response of the system to any input radiation. The present method opens up a new range of experiments where quasi-particles are used as probes. This pilot experiment on the *A-B* interface indicates that the method will work and further sophistication can now be considered. It is, of course, important to remember that the *A-B* interface in superfluid ^{3}He is unique in that it is a high symmetry interface between two very different but also high symmetry bose condensates. This is the most complex high symmetry interface to which we currently have experimental access.

Particle detection in superfluid ^{3}He

The work with the calibration of the black-body radiator, with its very high energy resolution led us to think that this device might provide a possible particle detector. We had suggested long ago [8] that superfluid ^{3}He would provide an ideal working material for the detection of low energy recoil interactions. The «working fluid» is simple, consist-

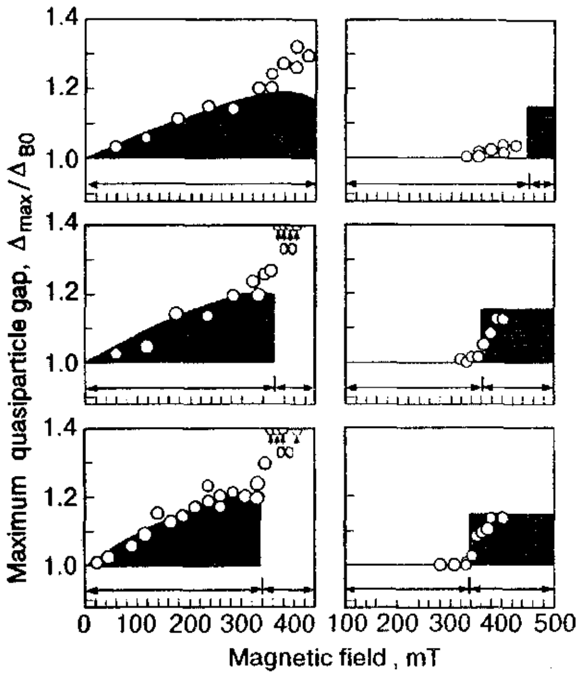

Fig. 12. The *A*- and *B*-phase gaps as measured in the *A-B* phase interface experiment (see text).

ing only of the superfluid ground state and the dilute gas of excitations. The excitations have energies comparable to that of the superfluid energy gap, $\Delta = 1.4 \cdot 10^{-7}$ eV, which is virtually the lowest which we can currently utilise. Finally, the only significant impurity in superfluid ^{3}He is ^{4}He. Extrapolation of the known high temperature solubility of ^{4}He in liquid ^{3}He to 100 μK suggests that ^{4}He is only soluble to one part in 10^{2000}. The purity of the working fluid is thus absolute.

Our first attempt at such an experiment was to take the black-body radiator used for the Andreev reflection experiment described above and monitor the temperature inside the enclosure while exposing the cryostat to the output of an AmBe neutron source. What we would expect to see would be as follows: a particle interacts inside the box, heats the liquid (i.e. increases the excitation density) causing a sudden fall in the amplitude of the thermometer resonator. The excess excitations in the radiator enclosure so-produced subsequently diffuse out of the hole and the amplitude recovers exponentially. The time constant for the quasi-particles to leak out of the box is governed by the geometry and the hole size and in a typical experiment is a few tenths of a second at the lowest temperatures.

The size of the jumps in the thermometer trace can be calibrated in terms of deposited energy by the application of a short known pulse of heating to the heater wire in the enclosure. When exposed to a source the events can thus be calibrated and presented as a spectrum in the usual way. Figure 13 shows spectra for a gamma source, a neutron source, and a background spectrum for comparison taken in this way [9]. The neutron spectrum shows a very prominent peak at around ~ 800 keV which arises from low energy neutrons undergoing the nuclear reaction $n + {}^3_2\text{He} \to p + {}^3_1\text{H}$. This process releases an energy of 764 keV into the liquid.

When we used the device to monitor the background radiation level we found that we could resolve events releasing energies of only 500 eV. This is rather a good performance for a device which was not only not optimised but was not even intended for these experiments. With various improvements we are convinced that we could improve the performance by many orders of magnitude and have proposed a dark matter detector based on this principle [9].

Simulation of cosmic string creation

An interesting further application of the black-body radiator has been in the simulation of the creation of cosmic strings via the Kibble mechanism. This mechanism was first proposed by Kibble [10] to describe the creation of topological defects during the series of phase transitions which the Universe is thought to have undergone shortly after the Big Bang.

There are profound analogies between the structure of superfluid ^{3}He and the structure of the metric of the Universe. Owing to the spin and

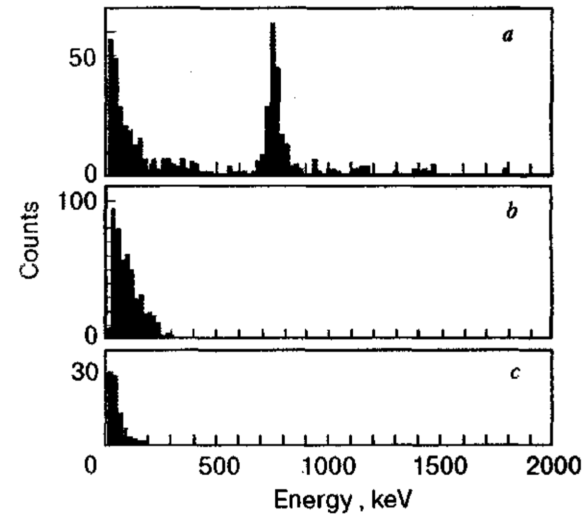

Fig. 13. Spectra of particle events measured in a black-body radiator in superfluid ^{3}He. The top spectrum is that taken with a neutron source, the middle that with a gamma ray source and the bottom is a background spectrum. The large peak in the neutron spectrum can be seen at around 800 keV which represents the neutron capture process (see text).

orbital angular momentum properties, ^{3}He shows a superposition of broken spin rotation, broken orbital rotation and broken gauge symmetries which provide a close approximation to the superposition of broken rotational and gauge symmetries used to describe the Universe. Similar types of linear defects (vortices), point defects (monopoles) and textures may be generated in superfluid ^{3}He in analogy with the various types of defects which may have been created (some of which may survive to the present) in the structure of the Universe.

The background of this experiment [11] depended on a certain level of serendipity. Fisher, working with Bunkov and Godfrin in Grenoble built an experiment similar to that used in Lancaster for the detection of neutrons [9], described above. However, the hole in the enclosure was made much smaller than that used in the Lancaster experiment. The smaller hole made this experiment less effective as a particle detector but allowed a much more accurate energy calibration to be made since the time constant of the system was much longer than that of the earlier version.

When a neutron interacted inside the black-body enclosure of the Grenoble experiment via the exothermic neutron capture process, the better calibration allowed us to ascertain that the energy taken up by the superfluid as thermal excitations was significantly lower than the 764 keV which is known to be released by this process. We know that some of this energy is released as ultraviolet photons which are lost to the helium. However, even after this fraction is taken into account there is still a significant «missing energy». It is this energy which we realized must have gone into producing topological defects in the liquid, in this case, vortices. The defects are formed when the liquid cools through the superfluid transition. The interaction of a neutron with a ^{3}He atom in the cold superfluid leads initially to the creation of a very energetic proton and tritium nucleus. These particles rapidly lose this energy to create a small volume of the liquid (a few microns in extent) which is heated above the transition temperature of 0.94 mK. As the liquid cools back through the transition, fluctuations in the temperature mean that many regions of the cooling «fireball» independently become superfluid and since these regions of superfluid are nucleated independently the order parameter is random. As the regions grow and coalesce grain boundaries in the order parameter are formed. These may relax to some extent by the bending of the order parameter but along every line around which there is a 2π circulation of the order parameter angle there is no

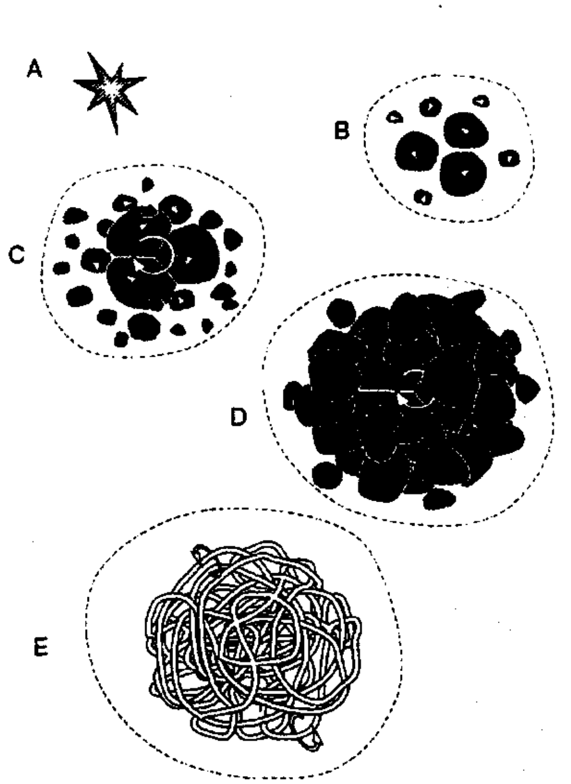

Fig. 14. Simulation of the creation of cosmic strings in superfluid ^{3}He. A small region of the liquid is heated by a neutron capture process. This leads to a small volume of the liquid being heated above the transition temperature. As this volume cools, independently-nucleated regions of superfluid are created. The order parameter in each «grain» is also independent. When the regions coalesce the mismatch of the order parameters leads to the formation of a vortex tangle.

possibility of relaxation and a vortex remains. The various domain contacts thus relax to form a vortex tangle. Since the background liquid is much colder than the transition temperature (around 100 μK compared with the transition temperature of 940 μK the vortex tangle is rapidly cooled through the region near the transition and reaches a temperature regime where the lifetime becomes very long. This process is shown schematically in Fig. 14.

Zurek [12] has translated the Kibble mechanism for application to phase transitions in quantum fluids. Zurek's scenario allows us to predict the density of topological defects as a function of the cooling rate and the characteristic time of the superfluid medium. We can independently estimate the typical distance apart of the topological defects, since we know the energy deposited in the liquid (the 764 keV released by the capture process). We can estimate from the liquid heat capacity what volume is heated above the transition and from the «missing energy» the length of vortex line can be calculated. When these two numbers are compared (of the order of 1 to 10 few coherence lengths in both cases) the agreement is found to be remarkably good [11].

Postamble

Much interest in the quantum fluids has been directed towards the behaviour at the higher temperatures where the order parameter is rapidly changing with temperature and the properties are dominated by the interplay between normal and superfluid components. For the «structureless» superfluids such as liquid ^{4}He and the conventional superconducting electron gas the low temperature regime might be thought of as of lesser interest as the condensate is so simple. Certainly in the case of superfluid ^{3}He the very low temperature regime is throwing up many interesting properties which have many implications for other areas of physics.

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