Evidence for Superfluidity in the Newly Found Phases of ^{3}He

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The relative viscosity η of liquid ^{3}He has been measured along the melting curve from 10 mK to about 1 mK with a vibrating-string viscometer. As the temperature is reduced, η first increases as expected until the pressure anomaly "A" is reached. The viscosity then starts to decrease, has a discontinuous drop at the pressure anomaly "B," and then continues to diminish rapidly. The lowest measured value of η is 1000 times smaller than that at point A. This must be regarded as strong evidence for superfluidity.

After the original discovery by Osheroff, Richardson, and Lee[1] a considerable amount of experimental and theoretical work[2-14] has been done in trying to explain the nature and the origin of the "A" and "B" transitions in ^{3}He below 3 mK. We have measured the relative viscosity η of liquid ^{3}He from 10 mK to well below these points. Our first results show several interesting features and strongly suggest that two superfluid transitions occur in the liquid below 3 mK.

The ^{3}He specimen was refrigerated inside a Pomeranchuk cell which had first been precooled to 15 mK by means of a dilution refrigerator. The cell has a total volume of about 3 cm^3 and it is made of two chambers connected via a 3-cm-long tube which has a diameter of 3 mm. The upper chamber, with a volume of about 2 cm^3, is equipped with a capacitive pressure gauge[15] and a vibrating-string viscometer.[16] The string, 2.5 cm long, 0.25 mm thick, and made of NbTi wire, is under a tension of 16 N which gives the system a natural oscillation frequency of 1245 Hz and an intrinsic Q of about 1000. An ac current of 2 mA is passed through the string.

It was expected that frictional heating and the magnetic field of 0.1 T required to operate the viscometer might promote the formation of solid ^{3}He around the string which, in turn, would prevent the viscometer from working. For this reason a superconducting solenoid, capable of producing a sharply profiled field up to 4.5 T, was fitted around the lower part of the ^{3}He cell. It was hoped in this way to restrict the solid to the lower chamber only, at least at the beginning of a compressional cooling experiment.

Runs were made in the conventional way by reducing the ^{3}He volume at a steady rate with the aid of a ^{4}He pressurizer. During an experiment the ^{3}He pressure was continuously measured with a General Radio 1620-A capacitance bridge with phase-sensitive detection. The viscosity was monitored by sweeping the viscometer ac excitation current semicontinuously through the resonant frequency. Since the signal amplitude, frequency shift at the resonance, and the width of the resonance line are all related to the viscosity and the density of the normal fluid, a considerable amount of information can be deduced from this type of measurement.[17]

Figure 1 illustrates the data obtained during one run, together with the simultaneously recorded pressure inside the ^{3}He cell. It is seen that, as the cooling proceeds after the melting curve has been reached at X, the signal amplitude decreases continuously and the resonant frequency is reduced, roughly in accordance with the expected $1/T^2$ temperature dependence for η. Immediately after the A transition this behavior is inverted. The amplitude starts to increase and the resonant frequency shifts upwards; this shows that damping of the viscometer string is decreasing. Exactly simultaneously with the pressure drop at B the vibration amplitude jumps discontinuously. After this has happened the amplitude increases very quickly and then remains constant as the temperature no longer decreases. Finally, at point Z the signal suddenly, in about 0.1 sec, completely disappears, presumably because solid ^{3}He starts forming on the wire.

So far we have made a dozen runs of the type illustrated in Fig. 1. The specific run shown was selected as an example because both the A and B transitions happen to occur near a resonance. In the other runs the overall behavior was very similar. During some experiments the viscometer string stuck soon after the A point was passed and in a few early experiments solid ^{3}He started to form inside the viscometer chamber before the A point had been reached.

Once the viscometer had stuck because of solid formation, the signal could be recovered by reducing the pressure; this apparently melted a

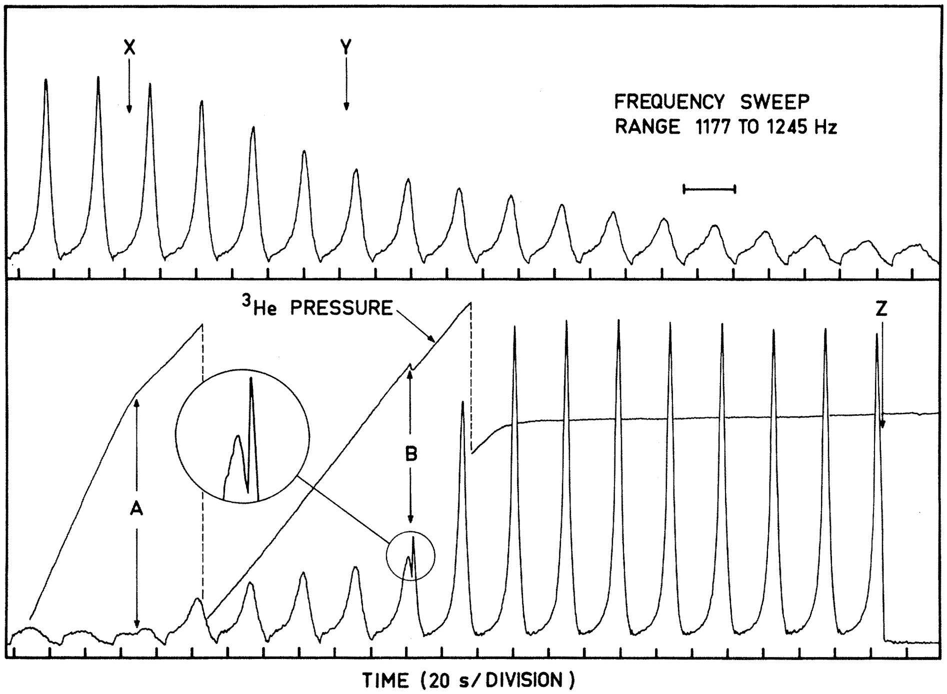

FIG. 1. Actual chart recorder tracing of the viscometer signal as a function of time. In the lower part of the figure the output from the capacitance bridge measuring the pressure in the ^{3}He cell is shown. The melting curve is reached and Pomeranchuk cooling starts operating at point X. At Y the compression speed is changed. The A and B transitions, and point Z, where the string sticks, are also marked. The inset shows the discontinuous increase of the viscometer signal at B. The slowness of the chart recorder pen does not give full justice to the magnitude of the discontinuity.

sufficient amount of solid in the upper chamber. When a second compressional cooling run was then made it was invariably found, however, that successful measurements of η through even the A transition could be performed only if the cell pressure had first been reduced below the melting curve and approximately 10 h had been spent on precooling. The importance of a low starting temperature, in the vicinity of 15 mK, was clear from our latest runs. They showed that measurements of η could be carried out up to the highest attainable pressure if during the last 4 h of precooling and during the compression itself the dilution refrigerator was operated in the single-cycle mode.

With a magnetic field on in the lower chamber the A transition was characteristically rounded and often seemed to occur with two discontinuities in the slope of the ^{3}He pressure-versus-time curve. This behavior is closely similar to that found by Osheroff, Gully, Richardson, and Lee[14] who recorded a splitting of the A transition in a magnetic field. Somewhat surprisingly, however, we noticed that the point at which the viscometer eventually became stuck could not be shifted in a reproducible manner by varying the field in the lower chamber. The main effect caused by an increase of the field was only a reduction in the cooling capacity and in the highest attainable pressure. As a rule, point B, with a sudden pressure drop, could not be reached unless the field was less than 0.9 T. The magnitude of the pressure drop ΔP_B was found to be about 0.6 mbar, and apparently was not dependent on the magnetic field. It is noteworthy that this is in disagreement with the data of Osheroff and coworkers[1,14] and of Halperin, Buhrman, Webb, and Richardson[6] who found $\Delta P_B = 0.3$ mbar and $\Delta P_B = 0.1$ mbar, respectively.

Results of several runs, with a 0.1-T field on the viscometer and with 0 and 0.6-T fields in the lower chamber, are shown in Fig. 2. As the melting pressure versus temperature relationship is inaccurately known at these temperatures, we present our data as functions of the relative ^{3}He pressure, referred to the A point. An analysis of the results shows, by assuming that the A transition always occurs at 2.6 mK and by em-

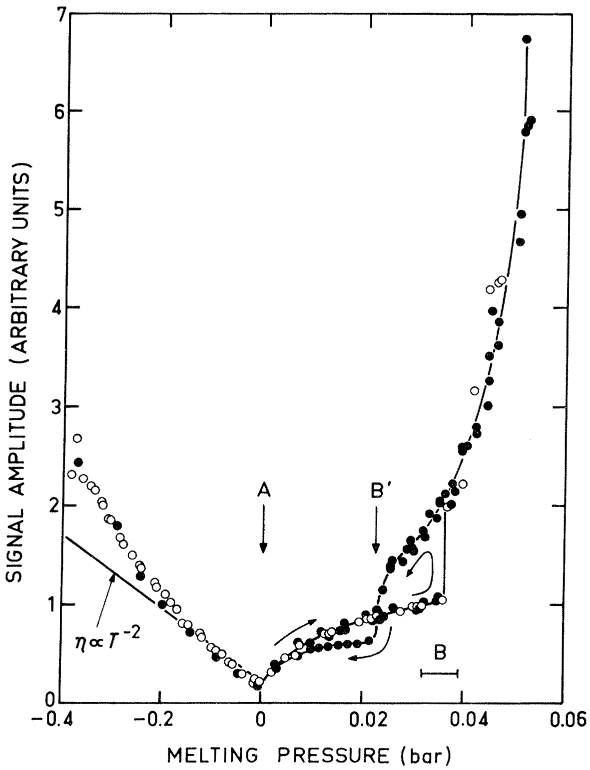

FIG. 2. Normalized viscometer signal amplitudes from six runs as functions of the ^{3}He melting pressure, with the zero set at the A transition. Note that the pressure scale is different on both sides of A and that the temperature decreases towards the right. To a reasonable approximation the signal amplitude should be proportional to $(1/\eta)^{1/2}$; the straight line to the left of A shows the expected behavior if ηT^2 = const. The double hysteresis loop, corresponding to compression through the A and B transitions and decompression through B' and A, is marked with bent arrows. The pressure interval at which the B transition occurs during the first compression of a run is also shown. Open circles, 0.6-T field in the lower chamber; closed circles, zero field in the lower chamber.

ploying the temperature derivative of the melting pressure as calculated by Goldstein,[18] that the data between 2.6 and 6 mK can be only roughly fitted with a $1/T^2$-dependent viscosity. All compressions were performed relatively fast compared with the thermal time constant τ ($\propto T^2$) of the liquid in the cell. Consequently, the rather large deviations from the $1/T^2$ behavior at the highest temperatures could be caused by the slow thermal relaxation, combined with inaccuracies of our temperature scale.

After point A (cf. Fig. 2) the signal increases with pressure. When point B', about 20 mbar above A, has been passed, the signal continues to increase relatively slowly until at point B the vibration amplitude jumps discontinuously and then increases rapidly to a value at which the signal somewhat later suddenly disappears. The location of point B varied considerably for different runs. The largest measured signal corresponds to a viscosity which is 1000 times smaller than that at point A.

During our latest runs we stopped compression soon after point B was passed, then reduced the pressure slowly, after which a new pressurization was started. By this procedure it was possible to traverse the hysteresis loop B-B'-A-B (cf. Fig. 2) repeatedly before the viscometer string eventually stuck. If the decompression was not carried much below B', then the pressure at which the B transition occured was each time closer to B' than before whereby the hysteresis B-B'-B finally almost disappeared. The drop of η at B simultaneously decreased. Within the limits of our resolution it seems that η changes rather steeply but continuously at B'. A surprising feature was that during decompression, between B' and A, the measured values of η fell consistently above the values recorded during the preceding (or subsequent) compression, and did not coincide with the upper curve (cf. Fig. 2) until the pressure was close to point A. We conclude that some kind of slow thermal relaxation within the liquid, and not simple supercooling, is responsible for the hysteresis B'-A-B'.

With our current knowledge of the physical properties of the newly found phases in liquid ^{3}He, it is not possible to attempt a detailed analysis of the results below 2.6 mK. Therefore, we adopt the simple two-fluid model of superfluidity which suggests the following conclusions: At point A the superfluid fraction of liquid ^{3}He starts to grow from zero as the temperature is lowered. Liquid states from B' to B correspond to supercooling as suggested by Osheroff, Gully, Richardson, and Lee.[5] At B, condensation into an energetically more favorable phase takes place and the superfluid density changes discontinuously. Finally, in the phase below point B the normal fluid disappears rapidly as the temperature is further lowered.

Although the viscosity of liquid ^{3}He changes profoundly at B it is not clear whether the associated pressure anomaly could occur in the liquid alone or whether it is brought about by ordering in the solid and/or by solid-liquid interactions.

The NMR resonance shift found by Osheroff *et* *al.*[5] and the discontinuity in the specific heat of liquid ^{3}He,[11,13] together with several theoretical predictions,[3,7-9] support the existence of an an isotropic superfluid ^{3}He below 2.6 mK due to a pairing type of condensation. Our viscosity measurements seem to give the most direct evidence for this hypothesis. The observed continuous viscosity with a discontinuity in $d\eta/dT$ at A and a rapid decrease of η below B seem to fit the suggestion by Anderson[7] that between A and B the liquid is a gapless superfluid (Anderson-Morel type) and that the transition at B leads to a superfluid with an energy gap (Balian-Werthamer type).

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Relaxation Time of the Cooper-Pair Density in Tin*

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The relaxation time τ_R for the density of superconducting electrons to achieve equilibrium with a change in current density has been measured near T_c, using a large, chopped dc and a small continuous rf current. The changeover from $\omega\tau_R \ll 1$ to $\omega\tau_R \gg 1$ has been observed in the frequency range 30 MHz $\leq f \leq$ 900 MHz. In the temperature range $0.95 \leq T/T_c \leq 0.995$, the relaxation time was found to be $\tau_R = 2.6\times 10^{-10}(1-T/T_c)^{-1/2}$ sec.

Recently, time-dependent phenomena[1-9] in superconductivity have attracted wide interest. Goldman and collaborators[4,5] have measured the lifetime of fluctuations in the gapless region above T_c by observing a voltage peak in tunneling experiments given by $V=\hbar/2e\tau_L$. In this case $\tau_L = \pi\hbar/8k_B T_c(T/T_c - 1)$ is the lifetime of the Cooper pairs. Clarke and Tinkham[6,7] have measured the time τ_Q for differences in the electronlike and holelike branches of the BCS spectrum to reach equilibrium. The detailed theory for this process has been given by Tinkham.[8] Gray, Long, and Adkins[9] measured the lifetime of quasiparticles at very low temperatures where the recombination is limited by the number of excited electrons present.

Here, we present the first determination near T_c of the relaxation time τ_R of Cooper pairs with change in current density. It has been known for a long time[10] that the superconducting wave function ψ decreases with supercurrent density j. If this is taken into account in the London equation $E=d(\Lambda j)/dt$, the value of the London constant Λ (which is proportional to ψ^{-2}) becomes dependent on the current density. If the current is the sum of a large (chopped) dc and a small rf current,