Observation of the Mechanical Response of the Condensate in He-*B* in the Regime of Negligible Normal Fluid Density

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Experiments are described in which superfluid ^{3}He-B is cooled to sufficiently low temperatures that the normal-fluid fraction becomes so small ($\rho_n/\rho < 10^{-6}$) that the quasiparticle properties become undetectable. The liquid ^{3}He is then effectively a thermal vacuum. In this regime nonlinear effects are observed in the behavior of a vibrating wire, effects which are not observed in an actual vacuum and which are evidently associated with the mechanical response of the B-phase superfluid texture.

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The outstanding feature of the superfluid phases of ^{3}He is the existence of directional properties in the order parameter, leading to the occurrence of textures. It is probably fair to say that theory has so far outstripped experiment in studies of these textures, since relevant experiments are not easy to set up. In superfluid ^{3}He-B particularly, the orientational effects on the texture of the experimentally available parameters (surfaces, magnetic fields, and superflow, for example) are rather subtle. Moreover, both experiment and theory have concentrated on the Ginzburg-Landau regime, just below the transition temperature T_c, since that is most readily accessible. Unfortunately any purely mechanical properties of the texture are completely swamped in the Ginzburg-Landau regime by the very strong mechanical damping of the quasiparticles, and most experimental work on textures has hitherto centered upon spin properties using NMR techniques.

However, if the temperature is reduced so far below T_c that the damping by the quasiparticles is negligibly small, a regime can be reached in which the mechanical properties of the superfluid condensate should be observable. The purpose of this Letter is to report measurements of this type using a vibrating wire as the experimental probe. Above $T_c/4$ the vibrating wire is strongly damped by the ^{3}He quasiparticles, but below $T_c/6$ the normal-fluid fraction is so small that the quasiparticle damping becomes entirely negligible. In the absence of any influence of the condensate, one would then expect to observe simply the (linear) vacuum damping of the wire. In fact, as the temperature is lowered below $T_c/6$, we see something quite different. Emerging above the decreasing quasiparticle damping, unusual nonlinear behavior of the wire is observed, indicating a mechanical response from the bare superfluid condensate.

In our experiments the ^{3}He sample and the refrigerant of 1-mm 99.99+%-pure Cu slabs coated with sintered silver are contained in a thin-walled paper-reinforced plastic box (the inner cell). This cell is furnished with a 1.5-mm-diam tower containing the Pt wires of an NMR thermometer which is coupled to the helium via a large sintered-silver pad. The viscometer is a 0.124-mm-diam Ta wire bowed into an approximate semicircle of diameter 8 mm and contained in a free volume such that all walls are at least 1 mm from the wire. The cell has a filling capillary of 1 m of 0.2-mm-i.d. Cu tube and is immersed directly into an outer cell also containing ^{3}He and packed with Cu flakes. In comparison with the more unusual bundle technique this method implies a large ^{3}He sample and a relatively small quantity of Cu refrigerant. The experiment is precooled to a temperature of around 10 mK in an rms field of 6.4 T. No special demagnetization profile need be used since the final ^{3}He temperature is determined by heat transfer from ^{3}He to Cu nuclei and is largely independent of the ideality of the demagnetization.

The final field serves three purposes simultaneously. Firstly, it provides the final field for the demagnetization and thus determines the temperature and heat capacity of the Cu refrigerant. Secondly, it provides the steady field for operating the viscometer, and finally it serves as the steady field for the Pt NMR thermometer. The Pt thermometer is operated at fixed frequencies and thus the final field is determined to be either 6 or 13 mT. These are relatively low fields for nuclear demagnetization but the heat leak into the Cu is low enough that in 13 mT temperatures below 200 μK can be maintained in the helium for several days. If the experiment does not require Pt NMR thermometry, then we may increase the final field to give a higher nuclear heat capacity, and the cold helium temperature can be held for a week or longer.

The final temperature reached by the helium and the thermometer in this experiment appears not to be limited by a conventional Kapitza resistance, but rather seems to be determined directly by the thermal properties of the ^{3}He. At 0 bar the thermometer cools to ~ 125 μK which corresponds to a normal-fluid density ρ_n of about 10^{-6} times the normal-state value ρ. At 7 bars on the other hand the thermometer only cools to some 220 μK which again corresponds to ρ_n/ρ of around 10^{-6}. The conclusion from this is rather daunting. Since at these temperatures the normal-fluid fraction falls by a factor of 10 for each 20 μK of cooling (at 0 bar) it is clear that the heat leak would have to be very substantially reduced for significantly lower temperatures to be achieved in ^{3}He-*B*.

As described previously,[1,2] a known alternating current of frequency f (Hz) is passed through the viscometer, and the in-phase and quadrature voltages developed by the movement of the wire in the steady field are measured. The frequency is slowly varied (increasing or decreasing) in order to determine the resonance line. The line may be conveniently characterized by the center frequency f_0 (corresponding to the maximum of the in-phase voltage, or the zero of the quadrature signal) and by the frequency width Δf_2 (taken as the frequency difference between the half-maximum points of the in-phase voltage).

At the lower temperatures, where the mean free path of the quasiparticles is much longer than the wire radius, the viscometer returns a width or damping proportional to the momentum of the quasiparticles, i.e., roughly proportional to the normal-fluid density.[2] At the lowest temperature reached the observed width of ~ 0.003 Hz represents a fall of more than 10^5 from the value at $T_c(P=0)$ of ~ 500 Hz as reported in Ref. 1. The intrinsic (nuisance) damping of the wire was measured in a separate experiment in a (partial) vacuum to be less than 0.009 Hz. The vacuum results (and all the measurements in ^{3}He where quasiparticle damping is observed) give the expected Lorentzian line shape associated with a linear harmonic oscillator.

It is in the region where the quasiparticle damping has virtually disappeared that the effects of the texture are seen. The response of the wire in this regime becomes markedly nonlinear. The first noticeable feature of the response is the line shape which becomes heavily skewed with a long tail on the high-frequency side and a rapid step on the low-frequency side. A number of scans through the line at 127 μK is shown in Fig. 1. The contribution to the width from the quasiparticles at this temperature and pressure is only 4×10^{-4} Hz. The high-frequency tail is exponential to within the accuracy of the data. The line shape appears to imply that there are two states of the motion. Either there is a response in which case the motion lies on the exponential part of the curve, or there is no response at all. As the frequency is swept up no response is observed until a threshold frequency is reached at which there is a jump to the exponential curve. This jump needs time to develop and it appears not to be the same for increasing and decreasing frequency sweeps. However, the behavior is *not* what would be expected from the hysteresis resulting from sweeping through the resonance of a strongly nonlinear oscillator, in which the line is skewed enough to be multiply valued over part of the range.[3] We have swept extremely slowly through the jump region (at about 2×10^{-7} Hz s^{-1}) and it appears that there might well be no hysteresis at all if the sweep were slow enough. A close examination of the slow sweeps in Fig. 1 reveals small cusps in the jump region which may indicate a cyclical approach to equilibrium.

The second unusual feature of the response is the behavior for different drive levels. If the excitation current is increased, then the exponential part of the line shape remains the same in

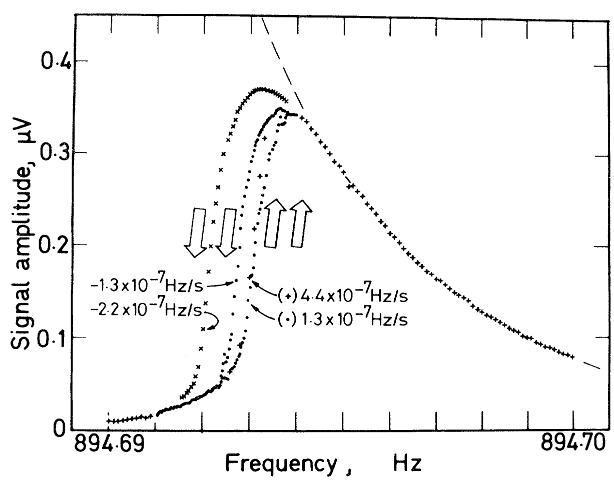

FIG. 1. The resonance line shape in ^{3}He-B ($P=0$, $T=127$ μK, $B=13$ mT) for a number of sweep rates. The dashed line is an exponential curve which fits the data on the high-frequency side.

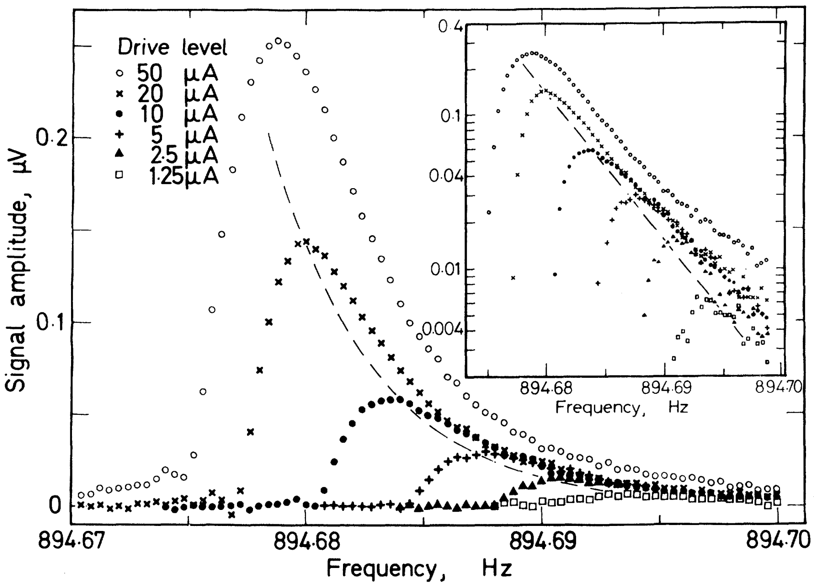

FIG. 2. The resonance line shape ($P=0$, $T=135\ \mu$K, $B=6$ mT) for a number of driving currents. Inset: The same data plotted logarithmically.

frequency and amplitude but the jump point moves to lower frequencies. A series of lines taken at different drive levels is plotted in Fig. 2 for $P=0$, $T=135\ \mu$K, and $B=6$ mT for decreasing frequency at 8×10^{-6} Hz s^{-1}. At the highest drive level dissipation is seen and the linewidth is increased. For the other drive levels the exponential part of the curve is *common* to all the lines. The jump at the low-frequency side appears rather indistinct in Fig. 2 since the sweep time (3600 s) was rather too fast for this feature to be resolved sharply. The inset in Fig. 2 shows the data plotted logarithmically, demonstrating the exponential nature of the line shape. Another way of describing the behavior is to consider the response at a fixed frequency as the drive is increased from zero. The response is zero until the drive reaches a critical value when oscillation suddenly begins with fixed amplitude which remains virtually constant (and apparently without dissipation) until finally the drive is high enough that dissipation occurs, the line broadens, and the amplitude increases again.

As the temperature increases the damping from the quasiparticles increases, and the nonlinear behavior is lost by about 180 μK for $P=0$ bar. A plot of central frequency against width Δf_2 (and thus by implication against temperature) is shown in Fig. 3 for several drive levels. The bulge in the data towards higher frequencies at Δf_2 above about 0.01 Hz is a result of the change in the line shape as the damping increases. The effect pulls the line to higher frequencies (as seen in Fig. 2 for the highest drive) as the width increases. The fact that the frequency increases for increasing T but decreases for increasing drive level essentially eliminates any possibility of a subtle heating effect being the cause of the nonlinearity.

Since one of the orienting forces on the texture is the magnetic field, we have also made measurements of the central frequency f_0 as a function of drive level at different magnetic fields (3, 6, 13, and 26 mT). An important correction

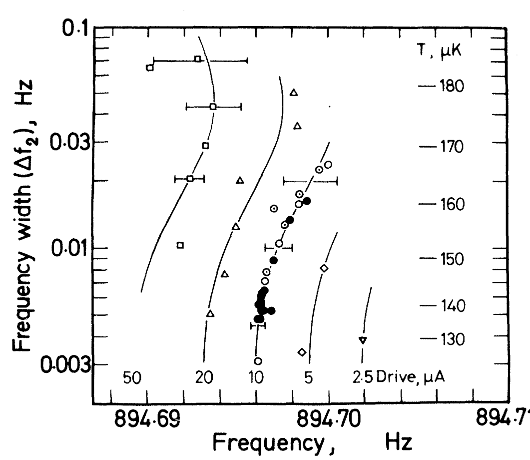

FIG. 3. The frequency width Δf_2 plotted against the central frequency f_0 for various drive levels, taken as the temperature increases ($P=0$, $B=13$ mT).

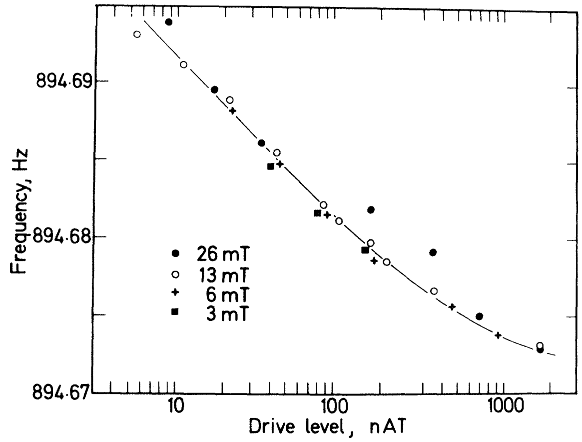

FIG. 4. The dependence of the central frequency f_0 on drive level for various magnetic fields ($P=0$, $T < 135\ \mu K$). The values of f_0 at 26 mT are less well defined since the resonance line was measured at fewer frequencies during this run.

is needed to compare values of f_0 at different fields. The use of a superconductor gives a small component to the restoring force on the wire from the compression of the magnetic field as the wire moves, causing an increase in f_0 proportional to B^2. This effect has been allowed for in the results plotted in Fig. 4, amounting to about 0.07 Hz at 26 mT, a figure consistent with direct measurements at higher fields and temperatures. Since the results superpose, there is no evidence of a dominant influence from the magnetic field. In addition the almost straight line verifies the linear dependence of f_0 on log(drive), linear until high enough drives produce measurable dissipation (at ~ 1000 nA T). A logarithmic relation of this type is hard to explain, since if it were to continue to infinitely low drives it would imply a divergence to an infinitely stiff system.

A less complete series of measurements at $P = 7.3$ bars shows similar features.

In summary, we have observed markedly nonlinear effects in a vibrating wire in superfluid ^{3}He-B at $T \ll T_c$ where the quasiparticle density effectively vanishes. The mechanism by which the superfluid texture affects the motion of the wire to give the asymmetric line shapes and the dependence of f_0 on drive level is not at all explained at present. As a starting point one can estimate the magnitude of the free-energy shift when ^{3}He-B is subjected to an appropriate flow velocity and magnetic field, and then compare this with the total flow energy of the superfluid. Our estimates, based on the work of Leggett,[4] Brinkman and Cross,[5] and Wölfle,[6] suggest that it will be difficult to account for the size of shifts in f_0 observed with this approach, although even here certainty is not possible since the currently known magnitudes refer only to the Ginzberg-Landau region, $T \lesssim T_c$. It seems probable that new ideas will be needed before an understanding is reached. We hope that these observations will stimulate theoretical interest in this aspect of textures. At the same time we are attempting to devise a probe which looks at the texture more directly and avoids the temporal and spatial velocity distribution of the vibrating wire.

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