# Evidence for Viscosity Reduction in Moderately Spin-Polarized $^3$He

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(Received 2 July 1986)

By use of the technique of rapidly melting moderately spin-polarized solid $^3$He, the viscosity of transiently produced spin-polarized liquid has been investigated. Partial melting makes a 10% polarized liquid near 50 mK with a viscosity decreased by 25% from the 8-T equilibrium value. Complete melting produces a liquid near 320 mK which shows no comparable polarization effect. These observations support a class of microscopic models in which the liquid is "nearly localized."

PACS numbers: 67.50.−b, 67.40.Pm, 67.65.+z

Observation of the effects of polarization on the thermodynamic and transport properties of liquid $^3$He provides key information concerning the proper microscopic picture for describing this strongly interacting Fermi liquid. One class of models views the effective interaction between the quasiparticle elementary excitations as dominated by spin fluctuations or paramagnons[1]; consistent with this, more sophisticated models predict that with increasing spin polarization the interaction should weaken, resulting in a decrease in the quasiparticle effective mass and the magnetic susceptibility and an increase in the mean free path.[2,3] Another class depicts the liquid as nearly localized and driven closer to localization[4] or perhaps even achieving a new localized state[5] with moderate polarization.

Unfortunately the liquid cannot be even moderately polarized in equilibrium with currently accessible magnetic fields. Castaing and Nozières proposed to produce polarized liquid transiently by rapidly melting the relatively easily polarized low-temperature solid.[6] Recent experiments[7,8] employing variations of the technique have been interpreted[9,10] as showing that the susceptibility, which is a measure of the polarization dependence of the internal energy, initially increases with polarization and may have a maximum near 20% polarization.

Partly motivated to investigate aspects of the melting process as well as to make viscosity measurements of the moderately polarized liquid, we have developed a tower on our compression-decompression cell which includes a vibrating-wire viscometer,[11] a carbon-resistor secondary thermometer, and a saddle coil for cw NMR measurement of the polarization. This is illustrated in Fig. 1. Much of the tower is filled with a Stycast 1266 epoxy plug, the same material that the body of the cell is made from. We calibrated the carbon resistor against the equilibrium $^3$He melting curve in the presence of an 8-T magnetic field which was present for all the measurements reported here. The cell was precooled by a dilution refrigerator to 30 mK and then thermally isolated by "opening" a Sn superconducting-normal heat switch. We assume that the equilibrium liquid susceptibility is the low-field value in the calibration of the NMR signal.

An ac current passing through the 0.159-mm-diam Formvar-coated NbTi wire viscometer causes it to vibrate as a result of the Lorentz force of the vertically oriented magnetic field. By Faraday's law the voltage across it is proportional to its actual displacement. The empty-cell resonant frequency is near 3.95 kHz with a quality factor $Q=600$. The viscosity of the liquid is derived by use of Stokes's solution for an infinite circular cylinder oscillating transversely in an infinite fluid.[12] The viscometer is normally operated in a self-resonating mode with constant drive amplitude; the resonant frequency and voltage amplitude are recorded. We use the full frequency response of the viscometer at selected temperatures and pressures to calibrate the device. In the range of viscosities reported here,

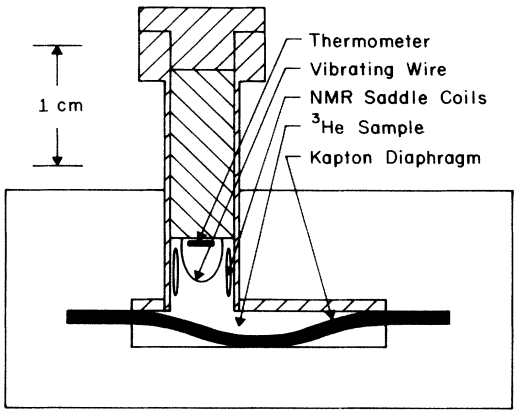


FIG. 1. The viscometer tower situated above the compression-decompression cell. The volume of the $^3$He sample is altered by a change in the pressure of $^4$He liquid occupying the volume below the Kapton diaphragm. Not shown are a pressure gauge, volume gauge, and sintered silver heat exchanger.

the resonant amplitude is proportional to $1/\sqrt{\eta}$ to leading order.

We show in Fig. 2 the viscosity $\eta$ and $\eta T^2$ for the equilibrium liquid at a pressure of 24.5 bars. In the low-temperature limit $\eta T^2$ should approach a nonzero constant for a normal Fermi liquid; our value for this agrees with previous measurements within the experimental uncertainty of 10%.[13,14] The dominant sources of uncertainty are in the determination of the effective diameter of the wire, since the determined viscosity depends on this to the second power, and in the fitting of the frequency-sweep calibration.[14] Fortunately neither of these effects enters as a consideration for the viscometer's resonant-amplitude changes seen during transient melting experiments.

The moderately polarized solid is produced by the Pomeranchuk effect: An initially all-liquid sample near 33 bars and 30 mK is compressed by a slow increase in the pressure of $^4$He pressurizing fluid on the bottom side of the Kapton diaphragm. Most solid forms near the spin-ordering region around 5 mK with an expected polarization greater than 60%. We estimate that between one-third and one-half of the sample in the viscometer tower solidifies during the complete solidification of the sample in the pancake-shaped volume. The details of this can vary from one compression to another, as further discussed in the next paragraph. This limited solidification has the disadvantage of restricting the maximum spin polarizations achievable in the tower; on the other hand, the heat capacity of the cold unpolarized liquid reduces the temperature rise in rapid melting experiments.

The behavior of the viscometer during the compressions proved to be very informative concerning how solid formed in the tower. The resonant frequency is very sensitive to solid formation. The onset of massive downward resonant-frequency shifts were accompanied by polarization growth seen by the NMR coil indicating that solid began growing on the wire. In some compressions massive upward frequency shifts were observed; these were not concurrent with polarization growth and were most common after short precools. We suspect that this latter behavior was due to solid formation at the base of the wire due to epoxy that was still warm. The viscometer's resonant amplitude is largely immune to solid formation until it abruptly stops as a result of being pinned by solid. Others have reported anomalous behavior of a wire viscometer in a Pomeranchuk cell.[15]

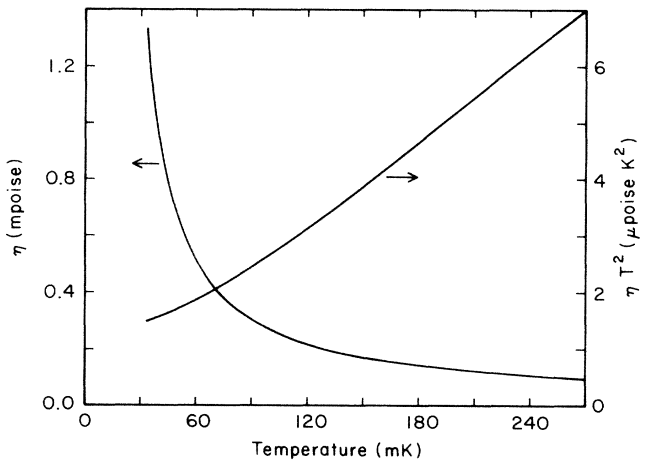


FIG. 2. The viscosity of liquid $^3$He at 24.5 bars. These equilibrium measurements in 8 T were taken during a slow precool. Normal Fermi-liquid theory predicts $1/T^2$ at low temperatures which is demonstrated in the $\eta T^2$ plot by a nonzero intercept.

In the work reported here we focus upon two particular decompressions. One was a total melting produced by dropping the $^4$He pressure to zero; the other was a partial melting accomplished by rapidly changing the $^4$He pressure from 24 to 19 bars. In both runs the viscometer quickly started to self-resonate and the resonant frequency showed no anomalous behavior; consequently, we trust the resonant amplitude to be a true measure of the viscosity of the liquid surrounding it.

Shown in Figs. 3(a) and 3(b) are the time traces of pressure, temperature, polarization, and the viscometer's resonant amplitude during these two decompressions. In the total melting [Fig. 3(a)], there is a pause in the pressure drop near 29.3 bars which we know from cell-volume measurements corresponds to where the last of the solid melts. This figure clearly indicates that enhanced polarization persists in the liquid for several minutes as others have previously observed.[11,16,17] The response time of the viscometer is seen to be a few seconds.

The rapid partial melting [(Fig. 3(b)] is qualitatively different in several ways. The pressure is seen to recover quickly from an undershoot of a few tenths of a bar; this unusual behavior was not present in previous measurements using this cell without the tower and may be related to the mixing of polarized and unpolarized liquids. About 10% of the sample melted and mixed with the unconverted cold and unpolarized liquid in the tower, thereby warming the tower sample by the reversed Pomeranchuk effect to 60 mK during the time of observation. As previously noted, the viscosity has a significant temperature dependence; however, the viscometer's resonant-amplitude trend is qualitatively opposite to that expected if it is a temperature effect.

The unusual behavior of the viscometer resonant amplitude in the partial melting experiment is most probably a polarization effect. From our equilibrium studies we can compute the equilibrium viscosity at all

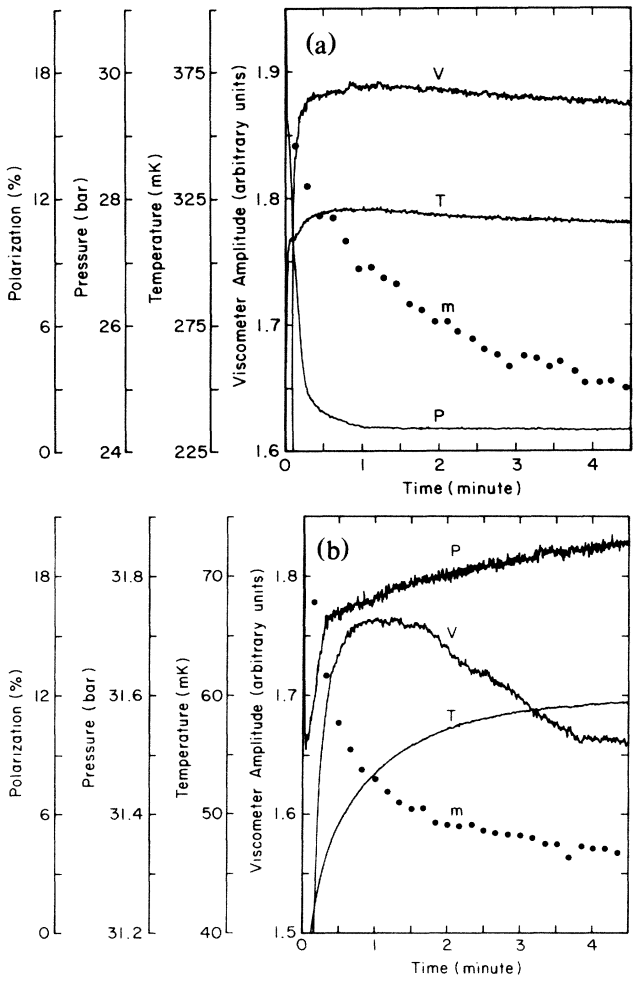


FIG. 3. Time traces of (a) a rapid complete melting and (b) rapid partial melting. $V$, viscometer's resonant amplitude; $T$, temperature; $m$, polarization; $P$, pressure. Pressure and temperature scales are very different in the two figures in order better to illustrate certain features. The behavior of the viscometer amplitude in the partial-melting experiment is interpreted as a decreasing viscosity with increasing polarization.

pressures and temperatures of interest here. Shown in Fig. 4 is the fractional change in viscosity versus polarization for the two experiments.[18] The very early behavior is not trustworthy and so the leveling off and apparent recovery of the low-temperature data for polarization above 10% should probably be ignored. Nevertheless, these data indicate that the low-temperature viscosity initially decreases with increasing polarization while at much higher temperatures no such effect is seen.

The microscopic models largely deal with the highly degenerate regime where, in particular, the viscosity should be following a $T^{-2}$ behavior. Similarly, the low-temperature behavior for the specific heat should

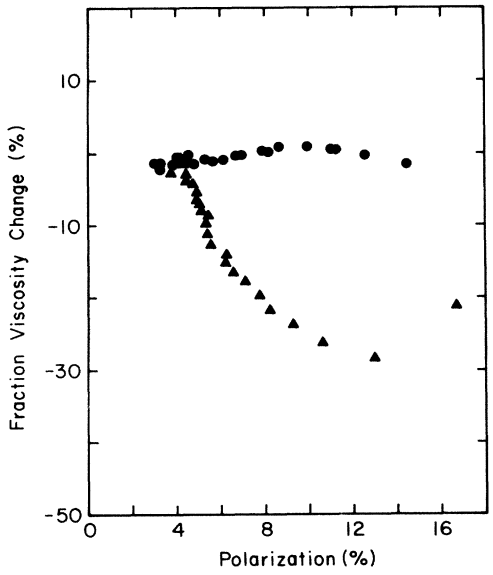


FIG. 4. Fractional viscosity change with spin polarization. By use of the temperature and pressure information during the melting experiments, the equilibrium viscosities are calculated and compared here with the observed viscosities. Circles, full melting; triangles, partial melting. Data for spin polarizations above 10% correspond to very early times after the cell expansion and cannot be trusted.

be a linear $T$ dependence. The major departure from linearity in the specific heat[19] near and above 100 mK has been interpreted as the "shaking off" of the spin-fluctuation cloud which renormalizes the quasiparticle effective mass for the very energetic quasiparticles present at high temperatures.[20] This explanation for the effects of temperature should be qualitatively correct for all classes of microscopic models. We speculate that similar reasoning should apply to the renormalized scattering amplitude which enters into the transport coefficients. This may explain the qualitative difference between our high- and low-temperature results.

In conclusion, for a degenerate Fermi liquid the viscosity can be written as

$$\eta = \tfrac{1}{5} n v_F l_\eta,$$

where $n$ is the number density, $v_F$ is the Fermi velocity, and $l_\eta$ is the viscous mean free path. With polarization, all of these parameters are expected to change but the biggest effect should be associated with $l_\eta$. Our experiments indicate that the viscosity and hence the viscous mean free path decrease with increasing polarization, suggesting that the system is becoming more localized. The size of the effect is sufficiently large that future experiments with a type of viscometer whose calibration is more accurate and less sensitive to magnetic fields should be able to observe the effect for

the lower polarizations of equilibrium liquid. Whether the trend continues with higher polarizations and possibly reveals a localized phase[5] or eventually reverses as the liquid becomes less interacting at high polarizations[4] should certainly be explored, but may require the production of low-entropy polarized solid by a nuclear demagnetization refrigerator in order to produce low-temperature highly polarized liquid.

We gratefully acknowledge valuable conversations with K. S. Bedell and G. Frossati. This material is based upon work supported by the National Science Foundation under Grant No. DMR-8218993.

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