Quantum Statistics and the Viscosity of Spin Polarized Liquid ^{3}He

O. Buu,* A. C. Forbes, L. Puech, and P. E. Wolf
Centre de Recherches sur les Très Basses Températures, laboratoire associé à l'Université Joseph Fourier, C.N.R.S.,
BP 166, 38042 Grenoble Cedex 9, France

(Received 30 April 1999)

Using the rapid melting technique to produce strongly polarized liquid ^{3}He, we have studied how polarization, through the Pauli principle, enhances the liquid viscosity in a wide range of pressures and temperatures ($2 < P < 27$ bars, $0.04 < T < 1.2$ K). Surprisingly, the viscosity enhancement is approximately linear in m^2, up to very large polarizations m ($m \approx 70\%$) and does not depend on pressure at low temperatures. Moreover, although the effect decreases with increasing temperature, it persists up to the largest temperatures studied. We discuss these findings in the context of the different descriptions of liquid ^{3}He.

PACS numbers: 67.65.+z, 66.20.+d, 75.10.Lp

The Pauli principle restricts binary collisions between identical fermions to an antisymmetric state. This makes the transport properties of dilute ^{3}He systems sensitive to the nuclear spin polarization of the ^{3}He atoms at temperatures low enough (smaller than 10 K) for their de Broglie wavelength to be comparable to their range of interaction. The effect is the strongest when the thermal velocity of atoms is so low that all collisions take place in a state of zero orbital momentum (s wave limit), i.e., in a singlet spin state. The mean free path should then be infinite for a fully polarized system [1,2]. In gaseous ^{3}He, this would occur below 0.1 K, i.e., at a vanishingly low density. At realistic temperatures, higher orbital moments come into play. More subtle effects are then predicted [3], and indeed observed [4], as an increase of the thermal conductivity upon polarization around 2 K. In contrast, the s wave limit can be experimentally realized in dilute, degenerate solutions of ^{3}He in ^{4}He, as, for concentrations smaller than 0.1%, the Fermi velocity is low enough for collisions to be dominantly s wave. This leads to a strong increase of viscosity with polarization [5]: the largest increase reported is by a factor of 3.5 at 4 mK and a nuclear polarization of 75% [6].

Can we expect similar effects to happen in a dense, correlated medium such as liquid ^{3}He? As the interatomic distance is comparable to the interaction range, it seems difficult to speak in terms of binary collisions here. It is, however, well known that, below 0.1–0.2 K, liquid ^{3}He is properly described as a gas of weakly interacting fermionic quasiparticles. Hence, it is not surprising that polarization does modify the viscosity of liquid ^{3}He, as is indeed observed [7,8]. Still, many fundamental questions are unanswered by previous experiments. First, at low temperature, how does the polarization effect depend on the pressure, that is, on the interaction strength? Second, does the polarization effect disappear at higher temperature, when the quasiparticle description breaks down? In other words, is the fermionic nature of ^{3}He still important under these conditions? The purpose of our experiment is to answer these questions, which, we hope, should help to discriminate among various microscopic models of liquid ^{3}He.

Large polarizations ($m > 10\%$) of the liquid can be produced only by out of equilibrium methods. We use the rapid melting technique [9], where solid ^{3}He is cooled below 8 mK in a 11 T magnetic field, corresponding to $m \approx 80\%$. Decompressing the solid by removing atoms to a room temperature volume yields transiently polarized liquid ^{3}He at any pressure below 29 bars, the minimum of the melting curve, but at high temperature (>200 mK), mostly due to the irreversibility of the melting process [10]. In order to cool the liquid in a time much shorter than the magnetic relaxation time T_1, we confine the experimental ^{3}He inside a silver sinter. Thanks to the sinter's large specific area and good thermal conductivity, the thermalization time ranges from 1 to 3 s, depending on pressure and temperature, while T_1 remains long enough (30 s at low pressure, 60 s at 27 bars) to allow experiments. This good thermal contact is decisive for our experiment. First, it enables us to obtain much larger polarizations at low temperature than was possible in previous viscosity measurements ($m < 20\%$ [7,8]). Next, it allows us to vary the temperature of the polarized liquid up to 1 K, in a time much shorter than T_1. Finally, it reduces the thermal gradients inside the cell, a critical issue as the viscosity depends strongly on temperature.

Figure 1 shows our experimental setup. The cell (0.1 cm^3 of ^{3}He) is screwed into a large heat tank (containing 4 cm^3 of unpolarized ^{3}He at saturated vapor pressure), itself connected to the mixing chamber of our dilution refrigerator. Both pieces were machined from 4N silver and annealed. ^{3}He in the heat tank fills 46 sintered holes (2.6 mm diam, 31 mm long), ensuring a fast heat transport. The experimental volume is a fully sintered, 4 mm diameter, 15 mm long, cylinder, cut by a 0.2 mm wide slit along its whole length. All sinters were made using 700 Å silver powder, at a filling fraction of 45%. Viscosity is measured using a vibrating Manganin wire,

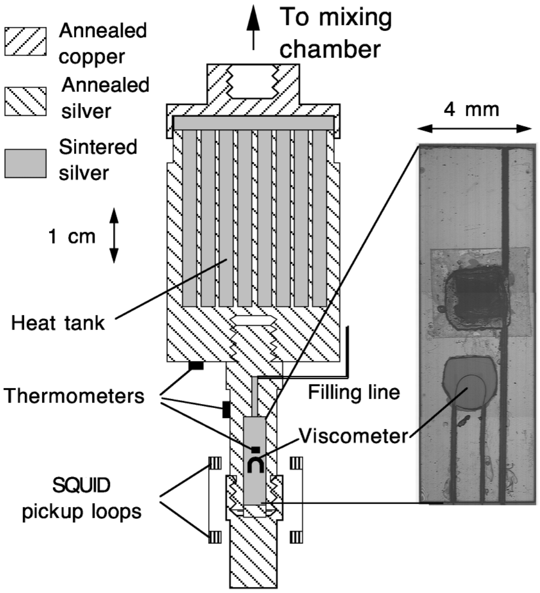

FIG. 1. The experimental setup and the sapphire slab supporting the 1 mm diameter viscometer loop.

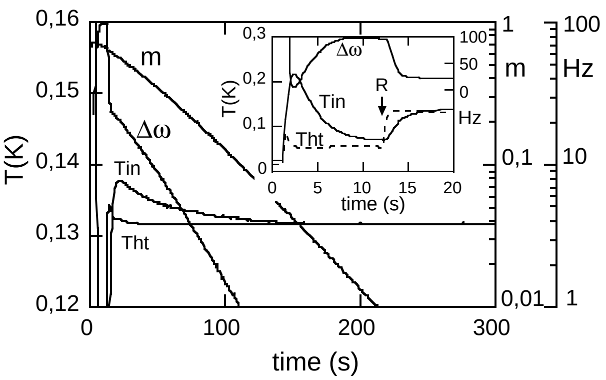

FIG. 2. Time dependence of the heat tank (T_{ht}) and cell inner (T_{in}) temperatures, ^{3}He polarization (m), and viscous damping resonance width ($\Delta\omega$; a base line of 48 Hz is subtracted) after a rapid melting down to $P = 10$ bars. Except at short times (inset) where they reflect temperature changes, the viscosity changes are mainly due to the polarization decay.

supported by a 170 μm thick sapphire slab. Its resonance frequency is ≈10 kHz, with $Q \approx 4000$ in vacuum. The slab also supports a thermometer ($0.07 \times 2 \times 2$ mm, sliced from a 100 Ω Speer resistor), hung 2 mm above the viscometer. After inserting the slab into the slit, the cell is sealed by gluing a 4 mm diameter silver disk onto the sinter.

We excite the wire motion by applying a 4 μA ac current at a constant frequency close to the "magic" frequency [11], where the phase is ≈45°, irrespective of the viscosity (if not too large). This gives a significant induced voltage at the wire terminals over the full viscosity range, although the resonance shifts as the viscosity varies. By measuring its in and out of phase components, we deduce the resonance width and the ^{3}He viscosity through Stokes formula [11] (the wire diameter, 30 μm, is small enough with respect to the slit width to avoid finite size effects on the flow pattern). A high field SQUID magnetometer [12] measures the average ^{3}He magnetization (the background contribution is less than 2% of the ^{3}He signal). The absolute polarization scale is determined by solidifying the experimental ^{3}He and measuring its Curie susceptibility as a function of temperature.

Figure 2 shows the measured signals during a typical experiment. At zero time, the cell filling line is decompressed. After a few seconds delay, ^{3}He inside the cell melts and the temperature rises. The cell is then cooled quickly by the heat tank down to between 40 and 60 mK, depending on the final pressure. During this step, the resonance width increases due to the viscosity increase upon cooling. We then regulate the heat tank at the desired final temperature (point R in Fig. 2). The whole process takes a short time with respect to T_1 (5 to 10 s). At longer times, the viscometer amplitude changes essentially reflect the decay of polarization, and, in a lesser manner, the slow cooling of the ^{3}He inside the cell, due to the decrease of the heat released by the spin relaxation [13]. By itself, the latter effect would cause an increase of the resonance width with time, whereas we observe a decrease, showing unambiguously that the viscosity increases with polarization.

In order to extract the effect of polarization alone, we normalize the viscosity measured during the relaxation to its equilibrium value at the temperature T_{in} simultaneously read by the inner thermometer (the temperature dependence at equilibrium being separately measured after each relaxation). The result at 27 bars and 80 mK is plotted in Fig. 3(A). The viscosity is observed to

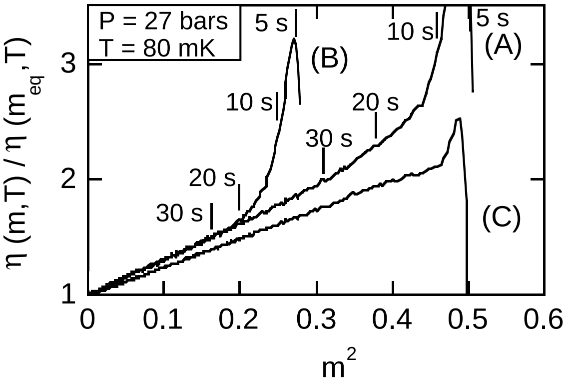

FIG. 3. (A) and (B): Polarization enhancement of the viscosity for two different initial polarizations. The enhancement is proportional to m^2. The peak observed at the shortest times is an artifact due to thermal gradients. Elapsed times are from the beginning of melting. (C): same as (A) taking the viscometer temperature equal to that of the heat tank, instead of the inner thermometer.

increase essentially as the square of polarization over a very large range of polarization (→ $m \approx 60\%$). The sharp rise at larger values is an artifact resulting from the fact that the thermometer initially cools more slowly than the viscometer. Indeed, repeating the experiment with a smaller solid polarization (B), we observe that the same sharp rise occurs in the same time range, for values of m where we know from the first experiment that the viscosity behaves smoothly.

Once the initial temperature difference has relaxed, the two curves are identical, although equal polarizations now correspond to different times. As the SQUID measures the average polarization whereas the viscometer is sensitive to the polarization inside the slit, this shows that the slit is narrow enough for the polarization to be homogeneous across the cell, despite the fact that the spins inside the slit have to diffuse inside the sinter in order to relax.

As in previous experiments [14], another source of error is a possible temperature difference between the viscometer and the thermometer, due to the heat released by the relaxation, in combination with different thermal resistances between these two probes and the isothermal cell silver walls. As this released heat, and, hence, the error, would depend on polarization only, it cannot be ruled out by the identity of curves (A) and (B) in Fig. 3. An upper bound of the possible error due to this effect is provided by curve (C) in Fig. 3, which we determined from experiment (A), now assuming the viscometer to be at the heat tank temperature (T_{ht}). This decreases the magnitude of the effect by about 20%, a moderate correction thanks to the good thermal homogeneity specific of our cell design. By combining an experimental determination of the relevant thermal resistances with the knowledge of the heat released by relaxation [13], we have improved upon the above upper bound of error by estimating the maximal temperature difference between the viscometer and the inner thermometer to be less than 20% of ($T_{\mathrm{in}} - T_{\mathrm{ht}}$), for all temperatures below 150 mK (for larger temperatures, this source of error is completely negligible). The resulting estimation is included in the error bars in Fig. 5 below.

We can now describe how our results are sensitive to pressure and temperature. As shown in Fig. 4(a), the effect of polarization decreases as the temperature increases at 27 bars. This is true for other pressures as well. In order to quantify this dependence, we fit the measured viscosity enhancement to $\eta(m)/\eta(0) = 1 + \alpha(T,P)m^2$, for m ranging from its equilibrium value (<4%) up to 45%. Figure 5, which shows how α depends upon P and T, clearly exhibits the main findings of our work: (i) At low temperature, α approaches a constant limit. (ii) Within 10%, this limit does not depend on pressure, as is clear in Fig. 4(b). Its value is ≈ 3, consistent with the results of the previous experiments at large pressure $\alpha \approx 2 \pm 1$ [7], $\alpha \approx 3.5 \pm 1.5$ [8]. (iii) The decrease of α as the temperature increases is faster at larger pressures.

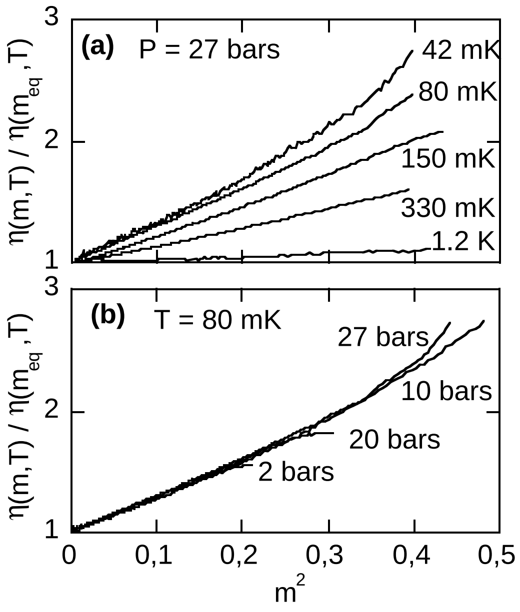

FIG. 4. Polarization enhancement of the viscosity for different (a) temperatures at 27 bars and (b) pressures at 80 mK.

Point (i) is not unexpected. Because of the weakness of the dipole-dipole interaction, binary collisions conserve the total spin. Hence, each spin stays on its own Fermi sphere, leading to the usual $1/T^2$ behavior of the viscosity at a low enough temperature. This implies that α should not depend on temperature in this limit.

In contrast, the lack of dependence of α with pressure (ii) is surprising. Liquid ^{3}He is often described as being close to an instability induced by repulsive interactions. In the nearly ferromagnetic model, polarization increases the viscosity by quenching the spin fluctuations (or paramagnons) responsible for the scattering of ^{3}He atoms [15]. An explicit calculation [15] in this framework

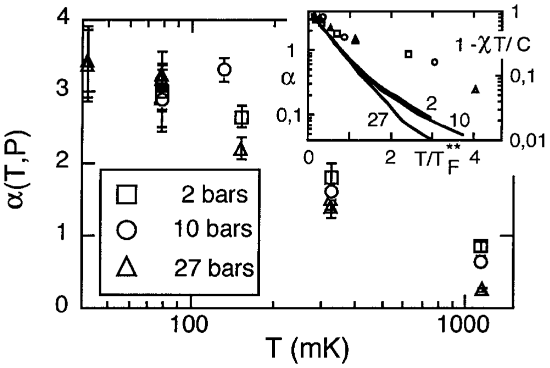

FIG. 5. Temperature dependence of the polarization effect (measured by α), for the various pressures studied. Inset: the same data plotted versus T/T_F^{**} decay slower than the deviation of the susceptibility from the Curie law.

predicts that α is proportional to the Stoner factor S (the enhancement of the magnetic susceptibility with respect to its ideal gas value), which increases by a factor of 2 from 2 to 27 bars. This is at variance with our experimental results. In the nearly localized model [16], there is no such explicit prediction. Quite generally, however, it seems to us that a pressure independent α means, that either ^{3}He is not close to an instability, or, at least, the viscosity is not sensitive to such a proximity. A natural question then is whether the observed behavior is consistent with the Landau theory. As a first step, it is striking that our results at low temperature are qualitatively accounted for by the expected behavior for a gas of weakly interacting fermions in the limit of pure s wave collisions [1], $\eta(m)/\eta(0) \approx 1 + \alpha m^2 + \beta m^4$, with $\alpha \approx 2$ and $\beta \approx 5$, independently of interactions. The fact that we observe a larger α (3) and a smaller β (<3) is not unexpected: First, the description of transport in liquid ^{3}He requires one to take into account both s and p waves [17], and, second, the quasiparticles themselves, unlike in a real gas, can be affected by the polarization. A detailed comparison thus requires to take into account the influence of polarization on the collision probabilities and the effective masses of up and down spins [18]. It would be interesting to develop such a calculation, assuming the minimal polarization dependence of the Landau coefficients consistent with that known for the susceptibility [13] and the specific heat [19], in order to see whether the pressure independent, nearly pure m^2 behavior of the viscosity can be understood in such a framework.

Let us finally turn to point (iii). In a dilute gas [1], α would decrease only by a small amount when going from the degenerate to the nondegenerate regime (keeping the temperature low enough to stay in the s wave limit). The observed marked decrease of the polarization effect with increasing temperature is thus a clear consequence of the liquid being dense. Consistently, the effect decays faster at larger pressures. A detailed interpretation is difficult, as, above several hundred mK, the concept of quasiparticles is expected to lose its validity. However, it is remarkable that the effect of polarization on the viscosity decays much more slowly than the low field susceptibility χ [20] approaches the Curie limit $\chi = C/T$ (Fig. 5). This means that spin statistics remain important even at temperatures larger than the magnetic Fermi temperature $T_F^{**} = T_F/S$ (300 to 500 mK depending on pressure [20]). Although such an effect is well known for a gas in a regime of binary collisions [1,2], it is more surprising for a dense system. In any case, the clear effect of polarization around 300 mK shows that, unlike sometimes assumed [21], the plateau of specific heat in this region [22] cannot be understood in terms of a semiquantum liquid [23], where the fermionic nature of ^{3}He would be irrelevant.

In summary, we have shown that nuclear polarization increases the viscosity of liquid ^{3}He at all pressures and temperatures. Two surprises are the lack of dependence, at low temperature, of this effect on pressure, and its relatively slow decrease at larger temperatures. Their explanation is an open challenge for the theories of correlated fermions.

We acknowledge stimulating discussions with B. Castaing, C. Lhuillier, P. Nozières, and G. Vermeulen.

---

*Present address: University of Nottingham, School of Physics and Astronomy, Nottingham NG7 2RD, United Kingdom.

[1] E. P. Bashkin and A. E. Meyerovich, Adv. Phys. **30**, 1 (1981); Sov. Phys. JETP **47**, 992 (1978).

[2] C. Lhuillier and F. Laloë, J. Phys. (Paris) **40**, 239 (1979).

[3] C. Lhuillier, J. Phys. (Paris) **44**, 1 (1983).

[4] M. Leduc, P. J. Nacher, D. S. Betts, J. M. Daniels, G. Tastevin, and F. Laloë, Europhys. Lett. **4**, 59 (1987).

[5] D. Candela, L.-J. Wei, D. R. McAllaster, and W. J. Mullin, Phys. Rev. Lett. **67**, 330 (1991).

[6] J. R. Owers-Bradley, R. M. Bowley, J. H. Naish, P. J. Richardson, A. P. J. Voncken, and R. K. König, J. Low Temp. Phys. **110**, 321 (1998).

[7] G. A. Vermeulen *et al.*, Phys. Rev. Lett. **60**, 2315 (1988); J. Low Temp. Phys. **76**, 43 (1989).

[8] C. C. Kranenburg *et al.*, Phys. Rev. Lett. **61**, 1372 (1988); C. C. Kranenburg, L. P. Roobol, R. Jochemsen, and G. Frossati, J. Low Temp. Phys. **77**, 371 (1989).

[9] B. Castaing and P. Nozières, J. Phys. (Paris) **40**, 257 (1979).

[10] O. Buu, A. C. Forbes, L. Puech, and P. E. Wolf, J. Low Temp. Phys. **110**, 381 (1998).

[11] D. C. Carless, H. E. Hall, and J. R. Hook, J. Low Temp. Phys. **50**, 583 (1983).

[12] M. Bravin, S. A. J. Wiegers, P. E. Wolf, and L. Puech, J. Low Temp. Phys. **88**, 723 (1992).

[13] S. A. J. Wiegers, P. E. Wolf, and L. Puech, Phys. Rev. Lett. **66**, 2895 (1991).

[14] P. Kopietz, A. Dutta, and C. N. Archie, Phys. Rev. Lett. **57**, 1231 (1986).

[15] M. T. Béal-Monod, Phys. Rev. B **38**, 8801 (1988), and references therein.

[16] D. Vollhardt, Rev. Mod. Phys. **56**, 1 (1984).

[17] G. Baym and C. Pethick, *Landau Fermi-Liquid Theory* (Wiley, New York, 1991).

[18] D. W. Hess and K. F. Quader, Phys. Rev. B **36**, 756 (1987).

[19] O. Buu, L. Puech, and P. E. Wolf (to be published).

[20] H. Ramm, P. Pedroni, J. R. Thompson, and H. Meyer, J. Low Temp. Phys. **2**, 539 (1970).

[21] C. Lhuillier, in *Strongly Interacting Fermions and High T_c Superconductivity,* edited by B. Douçot and J. Zinn-Justin (Elsevier, Amsterdam, 1995), p. 406.

[22] D. S. Greywall, Phys. Rev. B **27**, 2747 (1983).

[23] A. F. Andreev and Yu. A. Kosevich, Sov. Phys. JETP **50**, 1218 (1979).